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FAKULTA ZEMĚDĚLSKÁ A TECHNOLOGICKÁ

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Habilitační práce

Půdoochranné technologie jako základ pro omezování degradace půdy vlivem vodní eroze

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Podpis

Poděkování

Na začátku bych rád poděkoval několika významným osobám, bez kterých bych nikdy nemohl habilitační práci dokončit. Dovolím si tyto osoby uvést jmenovitě s krátkým komentářem, protože to považuji za důležité.

prof. Ing. Miloslav Janeček, DrSc.

Pan profesor byl mým prvním školitelem v rámci doktorského studia na České zemědělské univerzitě v Praze (Fakulta životního prostředí). Velice si vážím jeho cenných rad a konzultací. Byl pro mě odrazovým můstkem do světa půdy a vědy. Pod vedením pana profesora vznikl můj první vědecký článek. Kromě odborného přínosu měl pan profesor velký vliv na můj další rozvoj, neboť mě odkázal do tehdejšího Výzkumného ústavu meliorací a ochrany půdy, v. v. i. (VÚMOP), kde jsem nejprve vypomáhal a následně začal pracovat.

doc. Ing. Jan Vopravil, Ph.D.

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doc. RNDr. Petr Bartoš, Ph.D.

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Kromě výše uvedených jmen nesmím zapomenout poděkovat ani všem dalším kolegům, kteří se podíleli na jednotlivých výzkumných aktivitách. V řadě případů se jednalo o společně trávený čas v terénu při odběrech vzorků, simulacích deště či při zpracovávání dat a tvorbě jednotlivých publikací. Děkuji!

Obsah

Úvod

„Národ, který ničí půdu, ničí sám sebe.“
(Franklin Delano Roosevelt)

Půda patří zcela jistě mezi nejcennější bohatství každého státu. Bohužel v minulosti, zejména v průběhu 20. století, se významnost a důležitost půdy v české společnosti pomalu vytrácela. To vedlo ke stavu, kdy zemědělské pozemky s úrodnou půdou byly obhospodařovány intenzivním zemědělstvím, které neodpovídá základním principům trvale udržitelného rozvoje. Výsledky intenzivního zemědělství se postupně projevily ve snížené úrodnosti a degradaci mnoha pozemků, znečištěním řek i dalších složek životního prostředí. Přitom samotná obnova centimetru kvalitní půdy trvá řadu let (v závislosti na podmínkách a stupni degradace).

Ve druhé polovině 20. století se u nás začaly objevovat názory na potřebu ochrany půdy před její degradací a určitou racionalizaci při hospodaření. Tyto názory postupně s určitými výkyvy sílí až do dnešní doby. V současnosti si již dle mého názoru dokáže značná část společnosti uvědomit, že budoucí rozvoj nelze provádět pouze za účelem maximalizace zisku. Kromě toho je nezbytné zohledňovat další parametry, mezi které patří i ochrana jednotlivých složek životního prostředí.

Znalosti v oblasti zemědělství se velice dynamicky prohlubují. Díky tomu je k dispozici celá řada odborných materiálů dokazujících, že je možné efektivně využívat při pěstování zemědělských plodin jiné než klasické konvenční agrotechnické postupy. Za určitých podmínek mohou být alternativní postupy ekonomicky výhodnější než konvenční (nižší počet pojezdů po pozemku, cílená a variabilní aplikace hnojiv apod.). V souvislosti s problematikou vodní eroze se takové agrotechnické postupy označují jako půdoochranné technologie. A právě půdoochranné technologie u erozně náchylných plodin jsou hlavním předmětem této habilitační práce. Ta je poskládána z jednotlivých odborných publikací zaměřených na problematiku degradace půdy a efektivitu půdoochranných technologií z pohledu vodní eroze a množství povrchového odtoku.

Při následném doporučování řádně ověřené půdoochranné technologie jsme s kolegy vždy kladli důraz na tři základní aspekty, které by měl půdoochranný agrotechnický způsob hospodaření splňovat: 1) zajištění dostatečných výnosů pro obživu, 2) ochrana půdy před degradací, 3) hospodaření za ekonomicky udržitelných podmínek. Pouze při splnění těchto aspektů lze agrotechnický postup považovat za trvale udržitelný s reálnou šancí na zavedení do běžné praxe.

Provádění zemědělské činnosti v dnešní době není jednoduché, neboť je pro splnění všech právních předpisů nezbytné dodržovat celou řadu měnících se opatření. Opatření související s problematikou vodní eroze se často vážou na využívání půdoochranných technologií. Hlavním cílem této habilitační práce je proto poskytnutí hlubších znalostí právě o půdoochranných způsobech hospodaření.

1 Půdní prostředí

Půda má v rámci ekosystému velmi důležitou roli (Haygarth a Ritz, 2009; Maes et al., 2016; McBratney et al., 2014). Vzniká na rozhraní mezi atmosférou, hydrosférou, litosférou a biosférou a tvoří svrchní obal Země (Bouma, 2010; Dominati et al., 2014). Její existence je jedním ze základních předpokladů veškerého pozemského života (Blanco a Lal, 2008). Právě na půdě je možné poukázat na složitost a komplexnost přírodních systémů. Věda zabývající se půdou znamená studium komplikovaných, vzájemně provázaných procesů týkajících se fyzikálních, chemických a biologických složek půdy (Shainberg, 2000). **Tradičně je půda v zemědělství považována za základní výrobní prostředek** (Morgan, 2009), kdy utváří prostředí pro růst zemědělských plodin (Larson a Pierce, 1991; Blanco a Lal, 2008). **Půda má řadu dalších neméně významných tzv. „mimoprodukčních" funkcí**. Jejich částečný přehled je uveden v knize *„Půda a její hodnocení v ČR – Díl I."* (Vopravil et al., 2010). V publikaci jsou uvedeny následující funkce:

filtrační funkce půdy – umožňuje vsak (infiltraci) vody do půdy. Při tomto procesu se voda obohacuje o látky obsažené v půdním prostředí a má schopnost je případně neutralizovat (např. kyselé srážky). Filtrační funkce půdy zásadním způsobem ovlivňuje dotaci, složení a kvalitu podzemních vod, pramenů, vodních toků a nádrží.

retenční a akumulační funkce půdy – je chápána jako retence vody v půdě, ale zadržovány jsou rovněž další látky. Mohou to být rostlinné živiny v organické hmotě nebo v minerálním sorpčním komplexu. Půda může také vázat různé znečišťující látky, polutanty či kontaminanty. Retenční potenciál půdy je obrovský.

pufrační schopnost půdy – tlumí dynamiku některých půdních vlastností. Pufrační funkce tlumí změny půdní reakce (okyselování, acidifikace), rychlé teplotní změny apod. Při výrazném poklesu půdní reakce vyvolané zvenčí se pufrační schopnost půdy snižuje.

transformační funkce půdy – zabezpečuje přeměnu látek v jejich cyklu, umožňuje procesy rozkladu, mineralizace a syntézy. Porušení této funkce může způsobovat znečištění půdy a půdní vody nebo problémy s výživou rostlin. Na transformační funkci navazuje funkce asanační.

asanační funkce – je součástí transformační funkce a často s ní bývá spojována. Svým významem zahrnuje procesy rozkladu a mineralizace živočišných (i lidských) organismů.

transportní funkce – umožňuje migraci látek v půdním prostředí a vzájemný přenos látek mezi pedosférou, hydrosférou a atmosférou. Transport látek probíhá vertikálně (nahoru do atmosféry, dolů do geologického podloží a podzemních vod) i paralelně s povrchem půdy (smyvem po povrchu, vnitropůdními toky v závislosti na reliéfu a klimatu). Nejčastějším transportním médiem je v půdě voda.

funkce půdy jako genové rezervy a prostředí pro živočichy – půda je životním prostorem a základem života všech suchozemských organismů. Pro dosažení optimálních půdních podmínek je nezbytná přítomnost organismů a mikroorganismů v půdním prostředí.

kulturní funkce půdy – díky půdě můžeme lépe porozumět historickému vývoji přírody a lidské činnosti. Půda má tu schopnost, že ve svých znacích archivuje a uchovává změny klimatu, vegetace. Do této oblasti rovněž spadají paleontologické a archeologické nálezy.

Všechny půdní funkce (produkční i mimoprodukční) jsou v úzkých vzájemných vztazích a jsou zranitelné degradačními procesy. K tomu, aby půda mohla plnit své funkce, nesmí být zásadním způsobem tyto vzájemné vztahy narušeny. Podle odhadů může jeden gram půdy obsahovat až miliardu bakteriálních buněk skládajících se z tisíců taxonů (Fierer, 2017). Právě stav půdní bioty je považován za jeden z nejvýznamnějších ukazatelů kvality půdy díky vysoké citlivosti na změny podmínek prostředí (Bastida et al., 2008; Kibblewhite et al., 2008; Bone et al., 2010).

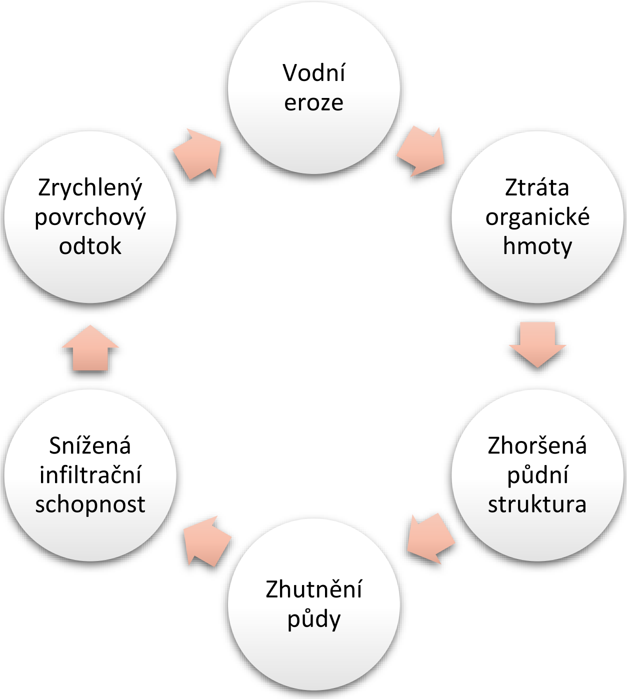
Je nesporné, že půdní prostředí má zcela zásadní roli ve stabilitě ekosystémů (Blanco a Lal, 2008). Na zemědělských půdách v případě nevhodně nastaveného osevního postupu a při využívání intenzivních agrotechnických postupů bývají složité půdní vztahy negativně ovlivněny. Výsledkem jsou zhoršené fyzikální, chemické a biologické vlastnosti půdy (Sheoran et al., 2019; Bedolla-Rivera et al., 2023). Půda na případné změny ve způsobu hospodaření, ať už pozitivní nebo negativní, reaguje obvykle pomalu. To je příčina, proč je někdy obtížné určit změny v půdním prostředí předtím, než dojde k výraznější degradaci (Nortcliff, 2002). Z tohoto důvodu je při hospodaření s půdou nezbytné uplatňovat dlouhodobý přístup zaměřený na zachování či postupné zvyšování půdní úrodnosti (Velten et al., 2015), neboť na degradované půdě je obtížné dosáhnout požadované produkce (Aleminev, 2024; Gao et al., 2025).

2 Degradace půdy

Celkový stav půdy a rozsah její degradace silně závisí na způsobu hospodaření (Blaikie a Brookfield, 1987; Bronnick a Lal, 2005). Případné narušení postihuje celý ekosystém (Robinson et al., 2013) včetně lidské společnosti a jejího zdraví (Oliver, 1997). Samotná degradace půdy obvykle znamená narušení či změnu půdních vlastností (fyzikálních, fyzikálně-chemických, chemických a biologických), což se projevuje v poklesu kvality půdy (Johnson et al., 1997; Lal, 2009). Degradaci půdy ovlivňuje mnoho činitelů. Mezi nejdůležitější řadíme trvale neudržitelné způsoby hospodaření (Dudka a Adriano, 1997). Zemědělství od svého vzniku v Neolitu prošlo řadou změn po celém světě. Výsledkem lidské činnosti byly postupné změny krajiny a životního prostředí (Bouma et al., 1998; Huntley et al., 2002; Kaplan et al., 2009). Ty se projevily v oblasti hydrologie, biologie, půdy apod. (Benito et al., 2010; Macklin et al., 2010). Dlouhodobá degradace půdy spočívá v postupném poklesu produkce a schopnosti půdy vyrovnávat se s případnými negativními vlivy (Lal, 2001; Oldeman, 1988).

Za hlavní půdní degradační procesy jsou považovány: eroze půdy způsobená vodou či větrem, extrémní půdní reakce (okyselování půd či jejich zasolování), degradace struktury půdy, nadměrné zhutnění a zamokření, půdní sucho, soliflukce, desertifikace, ztráta organické hmoty, biologická degradace, nepříznivé změny v obsahu a koloběhu živin, pokles pufrační schopnosti půdy nebo kontaminace přírodními a antropogenními zdroji (Blum, 1997; Várallya, 1989). Jednotlivé typy degradace spolu vzájemně souvisí. Převažující typ degradace podmiňuje vznik dalších typů a dochází tak k řetězové reakci, kterou je obtížné zastavit (MZe-a, 2018). Tato skutečnost je dobře zachycena na zjednodušeném schématu na obrázku 1.

Celosvětově je degradací ohroženo značné množství zemědělské půdy. Obecně se předpokládá, že je zasaženo některým z typů degradace přibližně 30 % zemského povrchu (Nkonya et al., 2016; Smith et al., 2024). Bai et al. (2008) uvádí ve své studii odhad podílu degradačních procesů na celkové degradaci půdy: vodní a větrná eroze až 83 %, nedostatek živin cca 4 %, nadměrné zasolení méně než 4 %, kontaminace půdy cca 1 %, špatná struktura půdy 4 %. Podobná čísla uvádí Lal (1994): vodní eroze 56 %, větrná eroze 28 %.



Obrázek 1: Provázanost jednotlivých degradačních procesů probíhajících v půdě.

Ve „*Zprávě o životním prostředí ČR*“ (MŽP-a, 2024), kterou pravidelně vydává Ministerstvo životního prostředí České republiky, je uvedeno, že vodní eroze je nejzávažnějším degradačním procesem v České republice. Potenciální ohrožení vodní erozí dosahuje 52,9 % celkové rozlohy zemědělského půdního fondu, přičemž v 18,2 % je ohroženo velmi silně. Z hlediska dalších degradačních procesů je ve zprávě uvedeno potenciální ohrožení větrnou erozí na 29,4 % území. Zhutněním půdy je ohroženo přibližně 40 % území (z toho 70 % způsobeno intenzivním zemědělstvím, 30 % genetickými vlastnostmi půdy). Obsah organické hmoty v půdě má nízký či nižší až střední celkem 55,8 % zemědělských ploch České republiky.

Rovněž je v situační zprávě uvedeno, že problémem je plošné znečištění pocházející zejména ze zemědělského hospodaření, neboť má významný vliv na jakost povrchových a podzemních vod (erozní splachy obsahující pesticidy, dusičnany a další látky). Zpráva dále obsahuje informaci, že celková ztráta půdy způsobená vodní erozí vzhledem ke změně klimatu vzroste do roku 2050 o 13-22,5 % ve srovnání s rokem 2016.

Aktuálně platný koncepční dokument Evropské komise „*EU Soil Strategy for 2030*“ (EU-a, 2021) vytyčuje střednědobé (do roku 2030) a dlouhodobé cíle (do roku 2050) týkající se ochrany a dobrého „zdraví“ půdy. Konkrétně je uvedeno, že základní vizí je, aby všechny půdní ekosystémy EU byly do roku 2050 ve „zdravém“ stavu. Do té doby by měla být ochrana a udržitelné využívání půdy standardní normou. Dokument uvádí, že půdu lze označit za „zdravou“, když je v dobrém chemickém, biologickém a fyzikálním stavu a pokud je schopna nepřetržitě poskytovat co nejvíce ekosystémových služeb. Jedním ze střednědobých cílů výše uvedeného dokumentu je obnova degradované půdy. Z hlediska dlouhodobého cíle je pak uvedena snaha o dosažení klimaticky neutrální Evropy, kde znečištění půdy bude na úrovni, která není škodlivá pro lidské zdraví.

Předpisem vycházejícím z výše uvedeného koncepčního dokumentu je směrnice „*Soil Monitoring Law*“ (EU-b, 2025). Základem tohoto předpisu je vytvoření jednotného systému pro monitorování a zlepšování zdraví půdy v EU. Důležitým nástrojem je rovněž „*EU Soil Strategy Actions Tracker*“ (Broothaerts et al., 2025), kde je cílem sledování postupu realizace jednotlivých kroků „*EU Soil Strategy for 2030*“ (EU-a, 2021). Jeho obsahem je 90 aktivit, u nichž je vždy uveden aktuální stav (dokončeno, probíhá, staženo). Ke konci roku 2025 je dle nástroje podíl dokončených aktivit na úrovni 70 %.

Všechna výše uvedená čísla a vize je potřeba brát s určitým nadhledem, neboť přesné vyčíslení rozsahu degradačních procesů je obtížné (Gomiero, 2016), stejně tak jako dosažení vytyčených cílů (Gao a Bryan, 2017). Přesto je správné, že podobné vize a dokumenty existují, neboť neřešená degradace půdy postupně vede k dlouhodobému poškození půdního fondu (Morgan, 2009).

Naštěstí ve vyspělém světě je snaha o výrazný posunu směrem k ochraně půdy a podpoře udržitelného hospodaření. Hlavní příčiny je možné shledávat v rozšiřování legislativních nařízení a předpisů zahrnujících ochranu půdy, optimalizaci managementu hospodaření, posuzování vlivů zemědělské činnosti na životní prostředí a jejich následné kvantifikaci (Fleming et al., 2000; Glasson et al., 2005; Nathanail a Bardos, 2005; Urusevskaya, 2007). Opatření týkající se ochrany půdy nicméně stále nejsou dostatečná (viz výše uvedené informace o stavu půdy z oficiálních dokumentů).

2.1 Vodní eroze jako jeden z degradačních procesů

Vodní eroze půdy patří mezi nejzávažnější degradační procesy (Boardman et al., 1990; Novara et al., 2011). Již ve druhé polovině 19. století byla eroze půdy považována za jeden z nejvýznamnějších environmentálních problémů (Bakker et al., 2007).

V souvislosti s erozí je potřeba si uvědomit, že jeden centimetr půdy se tvoří velmi dlouhou dobu. Následná obnova degradované půdy je proto obtížným a často nákladným procesem (Randolph, 2004). Erozi lze označit za přírodní proces, při kterém dochází k rozrušování povrchu půdy, transportu půdních částic a jejich následné sedimentaci v nižších polohách svahu. Smyté půdní částice jsou případně dále transportovány v hydrografické síti (Blanco a Lal, 2008; Piccarreta et al., 2012). Ačkoliv je výskyt vodní eroze stálý a přirozený jev, její rozsah je silně ovlivňován lidskou činností, obzvláště pak neudržitelným způsobem hospodaření (Boardman et al., 1990; Cerdà, 1994; Martínez-Casasnovas et al., 2016; Montgomery, 2007). Vodní eroze podpořená lidskou činností odnáší půdní částice v takovém rozsahu, že nestačí být nahrazeny přirozeným půdotvorným procesem (Vopravil et al., 2010).

Na výskyt vodní eroze má vliv celá řada ukazatelů. Mezi nejdůležitější patří: **topografické podmínky** (Cerdan et al., 2010; Koulouri a Giourga, 2007; Musgrave, 1947), kde rozhodující je velikost sklonu svahu a jeho délka (McCool, 1982; Koulouri a Giourga, 2007; Zachar, 2011); **způsob hospodaření** (Mondal et al., 2015); **vegetační pokryv půdy** (Paroissien et al., 2015); **náchylnost půdy k erozi** (Blanco a Lal, 2008); **intenzita deště** (Bouraoui et al., 2004; Tang et al., 2015; Zhang, 2012); **časové rozdělení srážek v průběhu roku** (Maeda et al., 2010). Pokud přívalové deště zasáhnou nechráněnou zemědělskou půdu, mají silné erozivní účinky. V takovém případě může dojít k výraznému snížení orniční vrstvy během relativně krátké doby. Díky vysoké intenzitě srážek dochází k překročení infiltrační kapacity půdy (Poesen et al., 2003), je snižována její saturační schopnost (Kirkbride a Reeves, 1993; Zachar, 2011), postupně je zvyšována půdní vlhkost (Imeson a Lavee, 1998; Nearing et al., 2004) a nastává povrchový odtok. V něm se vlivem kinetické energie srážek dopadajících na půdu akumulují oddělené půdní částice (Poesen et al., 2003). Tyto procesy následně vyvolávají vodní erozi půdy (Janeček, 2008; Mohamadi a Kavian, 2015).

Množství sedimentu v povrchovém odtoku je závislé nejen na uvolnění částic půdy srážkou, ale rovněž na rychlosti povrchového odtoku a vznikajícím tečném napětí na povrchu půdy (Morgan, 2009). V místě smyvu vzniká řada problémů v podobě zhoršených fyzikálních, chemických a biologických půdních vlastností (Lal et al., 2000). Eroze způsobuje řadu problémů také mimo zasažený pozemek. Příkladem je ukládání sedimentů v říčních korytech či zanášení vodních nádrží (Mullan, 2013). Do vodních toků se touto cestou dostávají těžké kovy, živiny z hnojiv či pesticidy.

To může vážným způsobem ovlivnit kvalitu vodních zdrojů (Vanmaercke et al., 2010), být příčinou vodní eutrofizace nebo negativním způsobem ovlivnit koloběh uhlíku, dusíku a fosforu (Chen et al., 2010; Quinton a Catt, 2007).

Při hodnocení rozsahu vodní eroze a jejího vlivu na půdní vlastnosti je potřeba počítat s velkou rozmanitostí půdního prostředí (Šimek et al., 2019). To, co platí pro jednu oblast, nemusí platit v oblasti jiné. Každé místo na naší planetě je svým způsobem jedinečné, a to samé platí pro půdu (Rejšek a Vácha, 2018). Změny půdních vlastností v důsledku eroze jsou dlouhodobým procesem (Duan et al., 2011) a zpravidla je nelze hodnotit v krátkých časových úsecích. Tato skutečnost nutně vede k určité nejistotě při měření půdních vlastností. Přesto je možné stanovit obecný vliv vodní eroze na některé půdní vlastnosti: 1) **v místě smyvu je snižována mocnost svrchní vrstvy půdy** (Lowery et al., 1995; Fullen a Brandsma, 1995; Arriaga et al., 2003). Je to jeden ze základních ukazatelů vodní eroze (Ebeid et al., 1995); 2) **obsah organické hmoty v půdě se působením eroze mění** (Papiernik et al., 2009; Šarapatka et al., 2018). Organická hmota je vyplavována a erodovaný pozemek se stává méně úrodným; 3) **má vliv na zastoupení zrnitostních frakcí v půdě** (Litaor, 1992; Fullen a Brandsma, 1995). Obecným předpokladem je, že nejprve jsou odnášeny jemnější částice. Až následně s rostoucím povrchovým odtokem a jeho transportními silami jsou postupně odnášeny těžší půdní částice (Pasák et al., 1984). Výsledkem může být vyšší štěrkovitost pozemku; 4) **svým působením ovlivňuje vodní eroze rozmístění i množství mikroorganismů v půdě** (García a Hernandéz, 1997). Rozmístění mikroorganismů do jisté míry odpovídá rozmístění organické hmoty, neboť mikroorganismy jsou její součástí. Část organické hmoty je navíc pro mikroorganismy potravou, a tudíž jejich četnost vzrůstá s růstem organické hmoty v půdě (Moreno-de las Heras, 2009; Mabuhay et al., 2006; Hou et al., 2014); 5) **vodní eroze má vliv na půdní reakci** (Gachene et al., 1997); 6) **během procesu eroze je měněna struktura půdy** (Packer et al., 1992; Bronick a Lal, 2005). Vliv vodní eroze na strukturu půdy je však těžko měřitelný, jelikož se týká prostorového uspořádání částic; 7) **vodní eroze ovlivňuje pórovitost půdy** (Abdullahi, 2018; Jankauskas et al., 2008; Ebeid et al., 1995); 8) **na erodovaném místě dochází k nadměrnému vyplavování chemických látek přítomných ve svrchní vrstvě půdy**. Zejména je vyplavován dusík a fosfor, ale i další chemické látky (Papiernik et al., 2009; Fullen a Brandsma, 1995); 9) **vodní eroze působí na retenční kapacitu půd** (Lowery et al., 1995). Spitz et al. (2000) uvádí závislost retenční kapacity půdy na hloubce půdy, zrnitostním složení, obsahu skeletu a humusu či na půdní struktuře. V důsledku toho je ovlivněna také retenční kapacita půdy.

Vodní eroze se dělí z hlediska rozsahu do několika forem. Podle metodiky „*Ochrana zemědělské půdy před erozí*" (MŽP-b, 2024) může být vodní eroze plošná, rýžková, brázdová, rýhová, výmolná a stržová. McCool a Williams (2008) uvádí, že základem vodní eroze je plošná a rýhová eroze. Za první fázi vodní eroze půdy je považována eroze plošná. Angulo-Martinez et al. (2012) ji definuje jako komplexní proces, který způsobuje oddělování půdních částic vlivem dopadajících dešťových kapek na povrch půdy a jejich následný přesun na krátkou vzdálenost (Jomaa et al., 2012; Hudson, 2006; Kinnell, 2005; Morgan, 2009; Ryżak et al., 2015; Sempere-Torres et al., 1994). Rýhová eroze nastává při soustředěném povrchovém odtoku (Poesen et al., 2003) a Valentin et al. (2005) ji označuje za hlavní formu eroze po celém světě. Půdy jsou takto nenávratně ochuzovány o orniční vrstvu (nejúrodnější část), což má negativní ekonomický dopad na uživatele půdy. Ten musí zvyšovat vnější vstupy do půdy s cílem udržet požadovanou úrodnost a zisk (Morgan, 2009). Zvyšovat vnější vstupy v podobě hnojiv a agrochemikálií nejde donekonečna. Pochopení procesů spojených s vodní erozí je klíčovým faktorem pro uplatňování správného protierozního hospodářského managementu (García-Díaz et al., 2017; Keesstra et al., 2016).

3 Půdoochranné technologie

Půdoochranná technologie představuje legislativně ukotvený pojem obsahující zemědělské postupy a opatření, jejichž základem je účinná ochrana půdy před degradačními procesy, respektive vodní erozí. Historicky nejsou půdoochranné technologie nijak zvlášť nové, neboť jejich cílené zavádění do systémů hospodaření je ve světě známé již od konce 40. let 20. století (Morgan, 2009; Montgomery, 2007; Cerdà et al., 2009). Půdoochranné způsoby hospodaření mají řadu přínosů, kdy hlavním cílem by měla být ochrana půdy před degradačními procesy (Ghimirey et al., 2024; Sadiq et al., 2025). Obecně splňují principy trvale udržitelného hospodaření, které má tři hlavní pilíře: zodpovědný přístup k půdě, zajištění ekologických funkcí krajiny a ekonomicky konkurenceschopná produkce (Smutný et al., 2015). Jako protiklad k půdoochranným technologiím je často dáváno konvenční zemědělství, neboť chápe půdu zejména jako výrobní složku a je často spojováno s negativními dopady na fyzikální, chemické a biologické vlastnosti půdy (Uri, 2000; Nail et al., 2007; Moussa-Machraoui et al., 2010).

Charakteristickým znakem půdoochranných technologií je ponechání zbytků předplodin nebo biomasy meziplodin na povrchu půdy, případně jejich mělké zapravení (Alberts a Niebling, 1994; Blanco a Lal, 2008). **Rostlinné zbytky na povrchu půdy přináší několik pozitivních efektů**: 1) **chrání půdu před dopadajícími kapkami** (Blavet et al., 2009; Jordán et al., 2010; Sadeghi et al., 2015), čímž dochází ke snížení povrchového odtoku a ztráty půdy (Cook et al., 2006; García-Orenes et al., 2012; Keesstra et al., 2016; Prosdocimi et al., 2016). Právě ztráta půdy a omezení povrchového odtoku patří mezi významné benefity rostlinných zbytků (Cerdà, 2001; Groen a Woods, 2008; Prats et al., 2014); 2) **zvyšují drsnost povrchu** (Cerdà, 2001; Jordán et al., 2010). Zdrsnělý povrch zpomaluje povrchový odtok a umožňuje zachytávání půdy a odnášených živin (Cerdà, 1998; Gholami et al., 2013); 3) **zvyšují infiltrační kapacitu** (Jordán et al., 2010; Wang et al., 2016) **a zásobu vody v půdě** (Cook et al., 2006; Mulumba a Lal, 2008); 4) **podporují biologickou aktivitu edafonu**, např. mikroorganismů, ale i samotných plodin (Fonte et al., 2010; Thierfelder et al., 2013); 5) **pozitivně ovlivňují celkový koloběh živin** (Campiglia et al., 2014); 6) **zlepšují stav půdní struktury a obsah organické hmoty v půdě** (De Silva a Cook, 2003; Karami et al., 2012); 7) **snižují objemovou hmotnost a zvyšují**

odolnost vůči zhutnění (Shahgholi a Janatkhah, 2018; Tang et al., 2024; Yan a Arthur, 2025); 8) **regulují svou přítomností teplotu svrchní vrstvy půdy**, což má pozitivní vliv na klíčení rostlin a rozvoj jejich kořenového systému (Dahiya et al., 2007; Riddle et al., 1996); 9) **snižují evaporaci** (Qin et al., 2006; Vanlauwe et al., 2015). Obecně je dalším benefitem půdoochranných technologií zlepšená půdní úrodnost a produktivita půdy (Kagabo et al., 2013). V neposlední řadě půdoochranné technologie udávají estetický ráz krajiny (Peng a Han, 2018).

Při půdoochranném způsobu hospodaření je často využíváno setí (sázení) do mulče a strniště. Termínem mulč je myšlen materiál na povrchu půdy, který chrání půdu a přispívá k růstu plodin (Jordán et al., 2011). Zpravidla se jedná o organický materiál tvořený posklizňovými zbytky předplodiny nebo o vymrzlou, případně chemicky umrtvenou meziplodinu. Při dlouhodobějším využívání meziplodin v osevních postupech se očekává příznivý vliv na výnosy hlavních plodin a celkovou kvalitu půdy (Javůrek a Vach, 2009). Mulč mohou rovněž tvořit biologické textilie, štěrk a kameny (Blavet et al., 2009; Jiménez et al., 2016; Jordán et al., 2010; Keizer et al., 2015).

V dnešní době existují vhodné půdoochranné technologie pro většinu erozně náchylných plodin pěstovaných v České republice. Půdoochranné technologie jako takové spadají mezi agrotechnická protierozní opatření (Hůla et al., 2003) a jsou určeny pro plodiny, které svým vzrůstem a zapojením nedostatečně kryjí půdu (kukuřice, čirok, brambory, cukrová řepa, slunečnice apod.). Před uznáním půdoochranného způsobu hospodaření je důležité, aby dostatečně chránil půdu před degradací a byl trvale ekonomicky udržitelný. To vyžaduje ověření půdoochranných systémů komplexním způsobem založeným na dlouhodobějším sledování (Schwilch et al., 2011).

Účinnost jednotlivých půdoochranných opatření je rozdílná, do značné míry závislá na půdně-klimatických podmínkách, kvalitě zapojení porostu v daném roce a samozřejmě i na intenzitě a četnosti výskytu konkrétních srážek (Vácha et al., 2019). Mezi dostatečně ověřené a velmi účinné půdoochranné technologie patří:

1. **přímé setí do nezpracované půdy (no-till)** – je určeno pro pozemky, kde byly pěstovány plodiny zanechávající strniště. Půdoochrannou účinnost lze zvýšit rozdrcením slámy při sklizni a jejím rovnoměrným rozptýlením po pozemku (Hůla et al., 2003). Hlavními přednostmi přímého setí do nezpracované půdy jsou vysoce

účinná protierozní ochrana, zvýšená schopnost půdy zadržovat vodu, snížené náklady pohonných hmot a úspora času potřebná na přípravu půdy (Blanco a Lal, 2008).

2. **setí s využitím mělké podmítky (reduced-till)** – základem je mělké zpracování půdy po sklizni s ponecháním maximálního množství rostlinných zbytků na povrchu půdy (Hůla et al., 2003). Pro podmítku jsou vhodné kypřiče s potlačeným mísícím účinkem (nedochází k promísení rostlinných zbytků a zeminy). Předpokladem úspěšného využívání technologie je kvalitní regulace plevelů a vzešlého výdrolu z předplodiny (Kovaříček et al., 2016).

3. **setí s využitím meziplodiny (reduced-till, i no-till)** – pro zkrácení období bez vegetačního pokryvu půdy se využívá agrotechnický postup založený na setí meziplodin po sklizni hlavní plodiny (Hůla et al., 2003). Vzniklá biomasa z meziplodin je pak zdrojem rostlinných zbytků, které mají silný protierozní efekt. Založení porostu meziplodiny by se mělo uskutečnit s minimální časovou prodlevou. Řešením může být současné zasetí meziplodiny během případné podmítky (Vácha et al., 2019). V takovém případě lze technologii řadit mezi reduced-till. Výsev meziplodin je však možný i bez podmítky. Pokud je setí meziplodin provedeno do nezpracované půdy, jedná se o no-till. Zde je obzvlášť důležité kvalitní ukončení porostu meziplodin (Wayman et al., 2015).

4. **pásové zpracování půdy („strip-till")** – obecným principem technologie je pásově zpracovaná půda v místě budoucího setí (Brant et al., 2016). Zpracovaný a nakypřený pás půdy poskytuje optimální podmínky pro vývoj zaseté plodiny, zatímco nezpracované pásy zůstávají pokryté rostlinnými zbytky (Menšík et al., 2018). Určitou nevýhodu představuje nutnost umrtvení porostu na nezpracovaném pásu. To lze provést různými způsoby (Willmott et al., 2025), nejčastěji desikací porostu (Alonso-Ayuso et al., 2020). Z hlediska protierozní účinnosti patří technologie pásového zpracování půdy mezi vysoce účinné půdoochranné opatření využitelné u celé řady zemědělských plodin (Morris et al., 2010). Nejvíce se u nás uplatňuje při pěstování kukuřice seté (Srbek et al., 2015). Mezi další plodiny pěstované tímto způsobem patří čirok, řepka, cukrová řepa, slunečnice, mák apod. (Brant et al., 2016).

5. **další vhodné půdoochranné agrotechnické postupy** – půdoochranné technologie nemusí být vždy založeny na rostlinných zbytcích na povrchu půdy (Rietra et al., 2022; Singh et al., 2025). Existují i další možnosti obhospodařování půdy, které jsou řazeny mezi půdoochranné technologie. Dle „*Metodické příručky pro podmíněnost*" (MZe-b, 2025) jsou za půdoochranné technologie považovány

následující postupy: vrstevnicové obdělávání pozemku; hloubkové kypření půdy s cílem rozrušit zhutnělou vrstvu a umožnit lepší vsak vody do půdy (nejčastěji podrývání u řepky ozimé a cukrové řepy); důlkování a hrázkování hrůbků u brambor; ochranné pásy tvořené travním porostem, pícninami či obilninami; obsetí hlavní plodiny ochrannými pásy; pěstování plodin s pomocnou plodinou; využívání podsevových plodin; pásové střídání plodin; a další (Novotný et al., 2017).

Při uplatňování půdoochranných technologií je nutné počítat s tím, že nemusí ochránit půdu před vznikem eroze za každé situace. Významným způsobem ale omezují rozsah následných degradačních procesů (Pimentel et al., 1995) a pomáhají snižovat vysoké finanční náklady spojené s obnovou degradované půdy (Blanco a Lal, 2008).

4 Komentovaný soubor prací

Cílem následujících kapitol je představení důležitých poznatků o půdoochranných technologiích a jejich přínosech ve vztahu k degradaci půdy vodní erozí. Každá z kapitol vždy obsahuje úvodní komentář, který následně odkazuje na publikace vydané v odborných časopisech (J_{imp}, J_{sc}).

Soubor prací tvoří celkem 14 odborných publikací. Část z nich se věnuje jednotlivým erozně náchylným plodinám. Mezi řešené plodiny uvedené v této habilitační práci patří: kukuřice setá, čirok, chmel otáčivý, brambory a cukrová řepa. Doplněna je i kapitola řešící povrchový odtok, neboť se jedná o nedílnou součást procesu vodní eroze. Každá publikace je uvedena v plném znění a je vytvořena dle požadavků daného časopisu. Zpravidla obsahuje úvodní část, metodický postup řešení, výsledky, diskuzi, závěr a seznam použité literatury.

V závěrečné části habilitační práce jsou uvedeny informace o výsledcích z aplikovaného výzkumu. Právě aplikované výsledky jsou důležitou součástí výzkumné činnosti. Díky nim je možné šířit informace mezi odbornou veřejnost a podpořit následný přenos poznatků do zemědělské praxe.

4.1 Kukuřice setá (*Zea Mays* L.)

Kukuřice setá patří mezi nejvýznamnější zemědělské plodiny pěstované po celém světě. Také v podmínkách České republiky zaujímá mezi zemědělskými plodinami důležité místo. Z pohledu pěstitelských nároků lze kukuřici považovat za teplomilnou plodinu vyžadující dostatek slunečního záření a tepla, obzvlášť v počátečních fázích růstu. Nejvhodnější jsou pro ni hluboké a úrodné půdy s dobrou zásobou živin a vododržností.

Kukuřice má díky vysokému výnosovému potenciálu široké možnosti využití: potravinářství, krmivo pro hospodářská zvířata, biopalivo či průmysl. Kromě širokého využití nabízí i široké možnosti v technologickém způsobu pěstování: konvenční (šířka řádku 75 cm), úzký řádek (šířka řádku 37,5 cm) či dvojřádek. Pro kukuřici existuje několik půdoochranných technologií, které pomáhají snižovat množství povrchového odtoku a rozsah vodní eroze. Mezi účinné půdoochranné technologie patří: no-till, no-till (úzký řádek), strip-till či využití podsevových plodin.

Konvenční pěstování kukuřice probíhá standardně ve vzdálenosti jednotlivých řádků 75 cm od sebe a je spojeno s nedostatečným pokryvem povrchu půdy, obzvlášť v období krátce po setí, neboť rostliny ještě nevytvářejí souvislý porost. Tato skutečnost výrazně zvyšuje možnost vzniku vodní eroze na svažitých pozemcích při výskytu přívalových dešťů. Riziko vzniku silné erozní události však přetrvává po celou dobu vegetace. To potvrzují data v závěrečné zprávě „*Monitoring eroze zemědělské půdy*“ (Kapička et al., 2024), kde je shrnuta situace týkající se erozních událostí v České republice. Vše je podpořeno aktuálně probíhající klimatickou změnou. Ta s sebou přináší častější výskyt extrémních srážek a období sucha. Z těchto důvodů by na svažitých pozemcích měly být uplatňovány půdoochranné technologie s cílem zajistit udržitelné pěstování.

Výsledky z výzkumu zaměřeného na protierozní účinnost jednotlivých způsobů pěstování kukuřice seté jsou uvedeny v **Publikaci 1**, která srovnává konvenční technologický postup s technologií no-till a strip-till. V **Publikaci 2** je pak dále podrobněji řešena technologie strip-till především z pohledu vlhkosti svrchní vrstvy půdy v průběhu vegetační sezóny kukuřice. Část výsledků spojených s kukuřicí je uvedena v **Publikaci 9** věnující se odtoku vody z krajiny, respektive metodě CN křivek.

Publikace 1

Název

The impact of the conservation tillage" maize into grass cover" on reducing the soil loss due to erosion.

Citace

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The impact of the conservation tillage "maize into grass cover" on reducing the soil loss due to erosion

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Abstract: Maize (*Zea mays* L.) belongs among the most important agriculture crops all over the world. The conventional way of cultivating maize with wide row spacing does not have a soil conservation effect and significantly contributes to water erosion and surface run-off. In our research, we tested the soil conservation technology (strip-till into grass cover) which took place in 2016 and 2017 in the location of Central Bohemia. The impact of a strip-till system of maize into grass cover on reducing the soil loss due to erosion was verified on the area of 21 m^2 using a rainfall simulator. During the research, 70 measurements were realised. The strip-till was compared to fallow land, conventional cultivation and no-till methods. Profound differences were found in the soil loss between the treatments. There was a decrease in the soil loss of about 98% in the strip-till compared to the conventional cultivation. Moreover, the surface run-off was reduced by 79%. The ANCOVA (analysis of covariance) models of the log-transformed soil loss on the surface run-off and treatment were highly significant ($P < 10^{-15}$). The measurement results clearly demonstrate the positive effect of the strip-till into the grass on the surface run-off and soil loss. This positive soil conservation effect was observed even in springtime, as well as the rest of the season. Using a grass cover for establishing the maize significantly contributes to the soil conservation on the land threatened by erosion and offers farmers a suitable way of farming when growing maize. Strip-tilling is a technology that has great potential in sustainable farming.

Keywords: erosion control measures; rainfall simulator; soil conservation; strip-till; surface run-off

Water erosion is a global problem (Novara et al. 2011) and causes destruction or damage to enormous areas of agricultural land every year (Morgan 2005). Agricultural land in the Czech Republic is largely exposed to the risk of water erosion due to the large land blocks, but also due to the agrotechnology used. More than half of the agricultural land is threatened by water erosion in the Czech Republic (Janeček 2005; Šarapatka & Bednář 2015). Soil degradation caused by water erosion is a complex process which

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depends on many factors (Cerdan et al. 2002), and is also very site dependent, mainly due to the differences in the soil climatic conditions (Davidová et al. 2015).

Over the past seventy years, large land degradation has taken place due to intensive farming, which is continuing presently. Agricultural subsidies have led to a significant increase in maize cultivation for the generation of energy from biomass in the Czech Republic. The expansion of maize acreage has resulted in the increased risk of water erosion due to the low vegetative soil cover after the sowing of the maize and the linear structure (Vogel et al. 2016). Brant et al. (2017) adds that the next major factor affecting arable soil erosion is large distance of the maize rows.

Within optimising cultivation systems of wide-strip crops (especially maize), new technological methods and procedures are being researched worldwide, which would ensure an increase in their energy and economic efficiency. In these technologies, under the conditions of European agriculture, a significant emphasis is put on eliminating the degradation of the soil processes, especially erosion, on increasing the infiltration abilities of the soils, on mitigating the technogenic soil compaction and on supporting the soil structure. One of the ways on how to fulfil the above-mentioned requirements is using a strip-till technology (Brant et al. 2016). Strip-tilling is a method of seedbed preparation in which confined strips of soil are tilled prior to planting. Seeds are then planted directly into the tilled strips, leaving inter-row areas protected by residue while avoiding residue contact with the seeds and seedling plants. Interest in strip-tilling has increased in recent years due to evidence that it combines many of the best aspects of the no-till and conventional cultivation systems (Randal & Hill 2000).

The main advantages of strip-tilling are obtaining a positive soil conservation effect as a result of the remaining crop residues in the inter-rows (Vyn & Raimbult 1993), improving the soil conditions for the crops' development in the rows and depositing fertilisers close to the roots (basic fertilisation and the application of nitrogen) enabling a reduction in their required amount. Another advantage is the more favourable conditions for sowing based on an earlier term for sowing compared to the no-till technology. Also, the strip-till technology has lower requirements in terms of the initial dosages of fertilisers compared to other technologies (Sundermeier et al. 2006).

Compared to conventional technologies, the application of a strip-till definitely leads to the overall decrease in the fuel consumption per area unit and, thus, to a reduction in the energy and economical inputs (Sundermeier et al. 2006; Brant et al. 2016). Various experiments with sowing maize into the cover crops (grass cover and fodder) with minimum soil treatment as protection of the slope areas against erosion and against washing-out the agrochemicals have been carried out in Switzerland (Rüttimann et al. 1995).

MATERIAL AND METHODS

The evaluation of soil conservation technologies for maize (*Zea mays* L.) in terms of soil conservation was carried out using a field rainfall simulator and also based on a soil survey and taking samples. The individual plots (established on an experimental areas) were compared with a control plot fallow. The magnitude of the surface run-off and soil loss due to the erosion were observed in the individual experiments. The verification of the technologies by the rainfall simulator took place in 2016 and 2017. The soil conservation technologies for the cultivating maize were established in cooperation with the cooperative farm Krásná Hora nad Vltavou, a joint-stock company in the Central Bohemian region. This cooperative is focused on animal production and it owns two bio-gas stations. The more frequent sowing of maize into the cropping system also follows from these activities (other crops in the crop rotation: canola, wheat, rye, sorghum, legumes).

Experimental areas. The study area is located in Central Bohemia (Czech Republic) at the experimental station of Skoupý (520 m a.s.l.). The climate is moderately warm with an average annual temperature of 7.5 °C and an annual precipitation of 550 mm (516 mm in 2016; 548 mm in 2017). The geographical coordinate system is 49°34'36.456''N, 14°20'44.084''E (Figure 1).

The soil type Cambisol was classified on all the experimental areas – the Main Soil Unit MSU 31. Based on the soil survey, it can be stated that the basic physical-chemical properties are similar in terms of the soils for the individual tested plots and, thus, the tested plots are comparable. The upper horizon of all the compared sites shows a texture type structure typical of sand-loamy soils. The basic soil properties: 1.27% total oxidizable carbon (C_{ox}); humus 2.19%; total nitrogen (N_{tot}) 0.156; C/N ratio 8.1. The topsoil layer is up to 30 cm (the soil texture: < 0.002 mm, 7.8%; < 0.01 mm, 15.5%; < 0.05 mm, 28.6%; < 0.1 mm,

https://doi.org/10.17221/25/2019-SWR

37.0%). The plots for the tested technologies were selected particularly for their uniform slope of 15%.

Field rainfall simulator. A rainfall simulator is a device which has been increasingly used to study soil erosion processes, and the use of rainfall simulators is widely accepted (Kovář et al. 2012; Ma et al. 2014; Lassu et al. 2015; Prosdocimi et al. 2017). The principle of measuring by a field rainfall simulator is based on the water spraying on a clearly defined and delimited area of 21 m^2, when the water jets, in a selected mode, spray water on the area for the whole measurement time. The rainfall simulator was situated down the slope just like the main crop with the strips of grass. The water spraying mode lasts for 30 min during the first rainfall simulation, then there is a 15-min technological break, after which the second rainfall simulation lasting 15 min follows. The intensity of the rainfall simulation was chosen based on the recommendation by the Czech Hydrometeorological Institute, based on the average intensity of torrential rainfalls in the Czech Republic. This intensity is considered to be 60 mm/h, and, during the mode construction, the condition (for the course of 15 min at least 6.25 mm) stated in the Guideline "Erosion Control in the Czech Republic – handbook" by Janeček et al. (2012) and Wischmeier and Smith (1978) was also taken into account.

The surface run-off and suspended solids in each variant were measured. The surface run-off was collected in a tipping bucket, which is a machine enabling one to measure the surface run-off. At constant time intervals of 3 minutes, the samples were taken into a calibrated container of 319 mL in size. The amount of the suspended solids for the particular variant was determined from the samples adjusted in this way.

Figure 1. The geographic location of the study area

Selection of the dates for the field experiment. The uniform and standard conditions on all the experimental plots were selected to verify the efficiency of the erosion control measures. The terms of the individual trials of the rainfall simulator are based on the terms of the growing periods given for the determining factor, the protective impact of the vegetation cover and the tillage method. The growing periods are defined in the Prediction Rainfall Erosion Losses from Cropland East of the Rocky Mountains: A Guide for Selection of Practices for Soil and Water Conservation (Wischmeier & Smith 1965).

I. the term of the rainfall simulation – in the period from the plot preparation for sowing up to one month after sowing

II. the term of the rainfall simulation – in the period for the course of the second month from the spring or summer sowing

III. the term of the rainfall simulation – in the period from the end of the second term of the rainfall simulation up to harvest.

Verified variants (no–till, strip-till, conventional cultivation, fallow land). The first selected variant in order to verify the soil conservation effect was the no-till technology. It was prepared into the cover of desiccated rye with 75 cm wide rows. The next technology was the strip-till (sowing maize into the tilled strip grass cover) with the row spacing of 75 cm. Both variants were compared with the conventional way of maize cultivation – classical tillage and also fallow land (maintained without vegetation). The sowing of maize took place on the 20^{th} of April 2016 and the 4^{th} of May 2017. A more detailed description of the agrotechnical operations is stated below:

The no-till sowing of the maize into the rye cover (width of row: 75 cm)

- in autumn, the crushing and shallow ploughing-in of the intercrop by a disc harrow takes place;
- followed by the vertical aeration to a depth of 20 cm;
- soil preparation before sowing by a compactor 1×;
- rye sowing by the no-till sowing machine until the end of September;
- in spring, the cover desiccation by a total herbicide;
- maize sowing by the no-till sowing machine into rows of 75 cm.

The maize sowing into treated grass strips – strip-till

- the areal desiccation of the grass cover by a total herbicide takes place in autumn;
- until the end of October, strip-tilling to a depth of 25 cm is made in the grass cover;

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– the plot is kept in this condition until spring;
– in spring, with the appropriate moisture, strip-tilling to a depth of 25 cm can be repeated if necessary;
– maize sowing by the no-till sowing machine into rows of 75 cm;
– the whole area with the grass is treated by the selective herbicide.

Conventional way of cultivating maize
– in autumn, the crushing and shallow ploughing-in of the intercrop by a disc harrow takes place;
– followed by the deep tillage of approx. 25–30 cm until the middle of November, without surface levelling;
– the tillage remains in a rough furrow until spring;
– in spring, soil treating by a compactor 2×;
– sowing maize into wide strips (75 cm) from the middle to the end of April.

Statistical analysis. Linear models were used to assess how the soil loss as well as its relationship with the infiltration differ in the different treatments. Since the preliminary analysis revealed a considerable heteroscedasticity and normality violation in all the models, the logarithmic transformation of the soil loss values was used as a response, after which both problems were eliminated. To avoid the problem with zeros, a small constant (0.001) was added to the soil loss values before the transformation. This constant was chosen by a trial-error inspection of the diagnostic plots checking for homoscedasticity and normality. ANOVA (analysis of variance) was used to test for the differences in the log soil loss means in the different treatments, followed by Tukey's multiple comparison. Then, we modelled the exponential relationship between the soil loss and the surface run-off in the different treatments by a linear ANCOVA (analysis of covariance) of the log-transformed soil loss on the run-off interacting with the treatment. The significance of the individual predictors was tested using ANOVA Type-II tests. The separate models were fitted for the first and the second rainfall in all the analyses. To test for the difference in the soil loss between the first and the second rainfall, we used the paired Wilcoxon test, using the original (i.e., untransformed) soil loss values. All the analyses and data manipulations were performed in the R statistical program (R Core Team 2017), with the use of the packages car (ANOVA Type II tests; Fox & Weisberg 2011) and agricolae (Tukey tests; de Mendiburu 2017).

RESULTS AND DISCUSSION

The results and evaluation of the terrain observation are based on the field experiments with the rainfall simulator and the laboratory measurements of the taken soil samples and the sediment. The following were evaluated for each variant: the magnitude of the surface run-off and the soil loss caused by the water erosion. Values of the surface run-off and the soil loss gradually decreased in the course of the maize growth. This was especially influenced by the crop engaging and also by the natural soil compaction. The data were evaluated separately in the first and the second rainfall simulation.

Profound differences were found in the soil loss between the treatments, both in the first and the second rainfall (see Table 1 and Figure 2).In the first rainfall, the highest and the lowest mean soil loss was recorded in the fallow land and the strip-till, respectively, and they differed by a factor of 46. In the second rainfall, the treatments with the highest and the lowest mean soil loss were the conventional cultivation and the strip-till, respectively, the former being 11 times higher than the latter. Interestingly, there were also similar differences in the soil loss variability, the standard deviations being always of the same order of magnitude as the means (Figure 2). Both in the first and the second rainfall, the treatment had a significant effect on the log-transformed soil loss ($P < 10^{-7}$), and it explained roughly 40% of its variability (multiple R^2 = 0.428 and 0.421 for the first and the second rainfall, respectively). Multiple

Table 1. The summary statistics of the soil loss under the different treatments and multiple comparisons of the results

Treatment	*n*	First rainfall				Second rainfall			
		mean	SD	mean log	hg	mean	SD	mean log	hg
Fallow land	19	6.673	6.922	1.114	a	0.484	0.650	1.114	a
Conventional cultivation	17	1.965	2.400	–0.479	a	1.727	1.948	–0.479	a
No till	16	0.836	1.390	–2.459	b	0.194	0.356	–2.459	b
Strip-till grass	18	0.144	0.235	–3.169	b	0.160	0.213	–3.169	b

n – the sample size (same for both rainfalls); SD – the standard deviation; mean log – the mean of the log-transformed soil loss; hg – the homogeneous groups based on Tukey's multiple comparison of the means of the log-transformed soil loss

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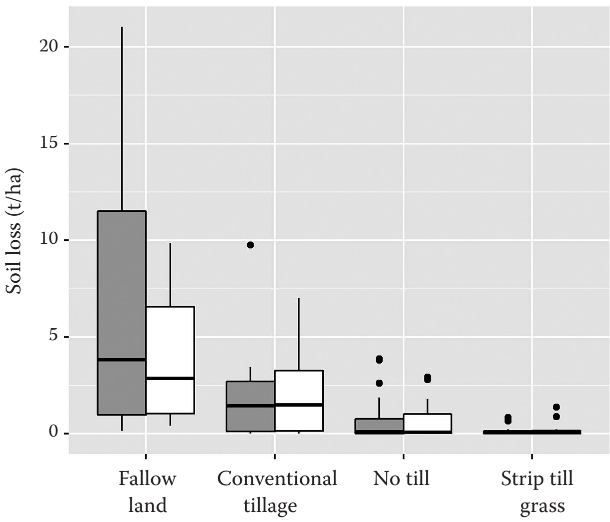

Figure 2. The quartile-based boxplots summarising the soil loss for the different treatments and the first (grey boxes) and the second (white boxes) rainfall

comparisons identified two homogeneous groups, identical in both rainfalls, with the fallow land and the conventional cultivation in one group and the strip-till grass together with the no-till in another group (Table 1). There was no significant overall difference (evaluated across all the treatments) in the soil loss between the first and the second rainfall (Wilcoxon statistic = 2 409.5, P = 0.866).

Generally, there is only little research in the strip-till technology into the grass cover. Our results are the first ones to provide information about the soil loss of the strip-till into the grass in the conditions of the Czech Republic. In the two-year measurements, a 98% decrease in the soil loss was achieved in the strip-till compared to the conventional cultivation. The soil loss was, in both research years, very similar without significant differences. Ryken et al. (2018) state a reduction of the soil loss in the strip-till technology (99%). Other results related to this technology were published by Wischmeier and Smith (1978). They determined the efficiency of the strip-till into the grass cover of between 95–97%. These results are not different from our values. Another research effort was recorded by Prasuhn (2012). In this case, a strong soil conservation effect was measured on the experimental plots in Switzerland. The soil loss achieved the value of 0.12 t/ha/year in the no-till (strip-till), while, in the plough tilled land, the soil loss was 1.24 t/ha/year. For the soil conservation technologies which include the strip-till, Wendt and Burwell (1985) recorded a reduction in the erosion higher than 90% compared to the conventional cultivation. Likewise, McGregor and Mutchler (1992) state a lower soil loss by 97% in the soil conservation technology.

The ANCOVA models of the log-transformed soil loss on the surface run-off and the treatment for the first and the second rainfall were both highly significant ($P < 10^{-15}$) and both explained 79% of the soil loss variability. The significance of the individual predictors and their interaction is summarised in Table 2, the regression lines back-transformed to the original scale are displayed in Figure 3. As expected, the surface run-off had a significant effect on the log soil loss (Table 2), all the slopes being positive (Figure 4). The surface run-off was reduced by 79% compared to the conventional tillage. In a similar way, Bosch et al. (2005) state that the surface run-off losses from the conventionally tilled plots exceeded those from the strip tilled plots by 81%. In both rainfalls, the regression slopes significantly varied between the treatments (see the significant interaction terms in Table 2), the fallow land having the lowest slope and the strip-till having the largest (Figure 4).

The presented results of the rainfall simulation show that the technology of the strip-till offers strong protection against water erosion. There is an increase in the surface water infiltration into the soil compared to the conventional cultivation. If a

Table 2. The analysis of variance tables for the ANCOVA (analysis of covariance) models of the log-transformed soil loss on the surface run-off interacting with the treatment

Source of variability	First rainfall			Second rainfall		
	sum of squares	*df*	*F* statistic[a]	sum of squares	*df*	*F* statistic[a]
Run-off	149.70	1	91.09***	130.64	1	94.36***
Treatment	21.73	3	4.41**	10.68	3	2.57
Run-off : treatment	22.93	3	4.65**	16.92	3	4.07*
Residual	101.90	62	–	85.84	62	–

df – the degrees of freedom; [a]*F* tests are of type II, following the principle of marginality; ***$P < 0.001$; **$0.001 < P < 0.01$; *$0.01 < P < 0.05$

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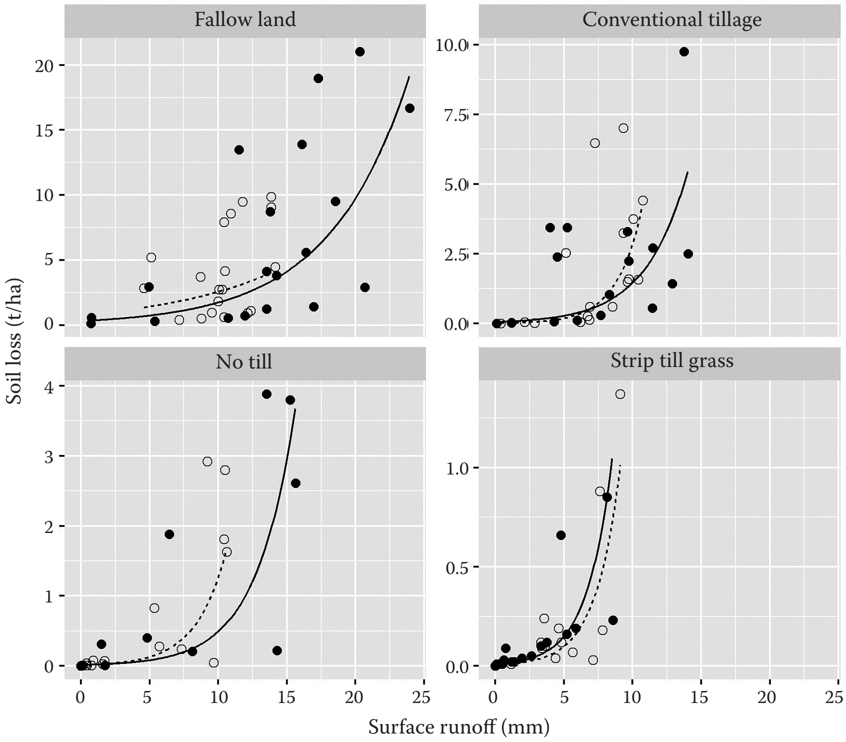

Figure 3. The relationships between the soil loss and the surface run-off for the different treatments, for the first (full circles and solid lines) and the second (open circles and dotted lines) rainfall

The lines represent the exponential regressions coming from the ANCOVA (analysis of covariance) models fitted separately for the first and the second rainfall data, with the log-transformed soil loss as a response and the surface run-off interacting with the treatment as the predictors

surface run-off occurs, the soil particles are released due to the strip-till from a significantly smaller area compared to the tillage.

The strip-till of the grass cover shows, in most cases of measuring zero soil loss values, when only clean water without sediments flowed from the soil surface. The fluctuations in the values in some measurements were influenced by the tractor tire track or by damaging the surface due to black game. All the experimental variants were prepared in the direction of the water flow line (down the slope). In practice, the leading grass strips in the direction of the contour line is expected, thus, achieving even better soil protection against erosion and surface run-off. Simultaneously, this technology supports the soil structure, reduces the evaporation from the soil, there is a better use of the nutrients from the applied fertilisers, which, in the final effect, contributes to a higher yield stability and production quality (Morrison 2002; Fernández et al. 2015).

Relatively favourable results were detected in the variant of the no-till into the rye cover. However,

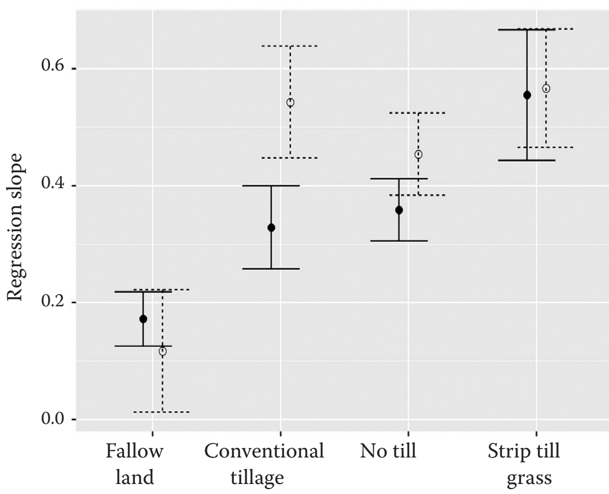

Figure 4. The estimates of the regression slopes and their standard errors from the linear regression of the log-transformed soil loss on the surface run-off for the different treatments

Data from the first (full circles and solid error bars) and the second (open circles and dotted error bars) rainfall experiments were analysed by separate ANCOVA (analysis of covariance) models

https://doi.org/10.17221/25/2019-SWR

it cannot be applied on all soil types. For example, in heavy loam soils there was a problem with the closure of the groove after sowing.

CONCLUSION

Maize is one of the most frequently grown agricultural crops in the Czech Republic. From the two years-worth of measurements it is apparent that the technologies for establishing maize into the grass strips provide a very strong soil conservation effect compared to the conventional technology. The soil loss was reduced to a minimum in the strip-till technology in all the realised measurements by the rainfall simulator. Also, the surface run-off was significantly reduced. On the other hand, the results of the conventional cultivation on the soil threatened by erosion show that the soil conservation effect is insufficient. When growing maize, the most prone period is the time after seeding. There is no soil conservation effect in the conventional technology because the plant cover is low. This is the main difference between the conventional technology and the strip-till into the grass. The strip-till technology has a positive conservation effect even in the springtime before sowing. The main aim of this paper was to introduce the results from the rainfall simulator measuring, as well as a new technological method on how to use grass covers for establishing maize and, thus, to contribute to the soil conservation on soils threatened by erosion. Due to the fact that the soil loss and surface run-off were lower throughout the season, it can be concluded that the strip-till is a suitable soil conservation technology for maize.

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Publikace 2

Název

Effect of different methods (conventional and strip-till) of maize cultivation on topsoil moisture and temperature.

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Effect of different methods (conventional and strip-till) of maize cultivation on topsoil moisture and temperature

Vliv různých způsobů (konvenční a strip-till) pěstování kukuřice na vlhkost a teplotu půdy ve svrchní vrstvě

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ABSTRACT

Soil moisture is an important factor that affects not only crop growth but also a wide range of soil parameters. Nowadays, most crops can be grown in different ways: for example, conventional and conservation techniques. Different cultivation systems also affect soil moisture. For this reason, the main focus of this paper is to compare conventional and strip-till techniques for growing maize (*Zea Mays* L.) in terms of their effect on topsoil moisture. These techniques were chosen primarily because of the significant difference in surface coverage by plant residues. The research was conducted between 2023 and 2024 at two locations in the Czech Republic. Soil moisture at a depth of 15 cm was monitored using moisture sensors with automatic recording throughout the maize growing season. Temperature was also measured in the same way. Due to the changing soil surface cover, the maize growing season was divided into three parts: the initial growth period, the period up to two months after sowing, and the period of full growth. The results show the different effects of the tested techniques on soil moisture, especially in the period shortly after sowing. The strip-till had statistically higher (P=0.05) soil moisture in both years compared to the conventional technique. This confirmed the positive effect on soil water content during the initial growth period of maize. In the remaining two periods, due to the gradual growth of maize and the decomposition of plant residues, the differences between the both techniques decreased. In the case of soil temperature, this is a more stable soil parameter which did not differ statistically between the techniques considered.

Keywords: conservation techniques, soil, soil cover, crop residues, corn, moisture sensor

ABSTRAKT

Vlhkost půdy je důležitým faktorem, který ovlivňuje nejen růst plodin, ale i celou řadu půdních parametrů. V dnešní době je možné většinu zemědělských plodin pěstovat různými způsoby: například konvenční a půdoochranný. Rozdílný technologický způsob pěstování ovlivňuje mimo jiné i půdní vlhkost. Z tohoto důvodu je hlavním předmětem článku porovnání konvenční technologie a technologie strip-till při pěstování kukuřice seté (*Zea Mays* L.) z hlediska jejich vlivu na půdní vlhkost ve svrchní vrstvě půdy. Tyto technologie byly vybrány kvůli výrazné odlišnosti v pokryvnosti povrchu rostlinnými zbytky. Výzkum probíhal v letech 2023-2024 na dvou lokalitách v České Republice. Vlhkost půdy v hloubce 15 cm byla sledována pomocí vlhkostních čidel s automatickým záznamem po celé vegetační období kukuřice seté. Stejným způsobem byla měřena i teplota. Vzhledem k měnící se pokryvnosti povrchu půdy bylo vegetační období kukuřice rozděleno na tři části: období počátečního růstu, období do dvou měsíců od setí, období plného vzrůstu. Z výsledků je patrný rozdílný vliv technologií na půdní vlhkost v období krátce po setí. Technologie strip-till měla v obou letech statisticky vyšší (P=0.05) vlhkost ve srovnání s konvenční technologií. Potvrdil se tak pozitivní efekt na obsah vody v půdě v počátečním růstu kukuřice. Ve zbylých dvou obdobích se vlivem postupného růstu rostlin a rozkladem posklizňových zbytků rozdíly mezi technologiemi snižovaly. V případě teploty půdy lze konstatovat, že se jedná o stálejší půdní parametr, který se u posuzovaných technologií statisticky nelišil.

Klíčová slova: ůdoochranné technologie, půda, pokryvnost půdy, rostlinné zbytky, kukuřice, vlhkostní senzor

INTRODUCTION

Soil moisture and soil temperature are very important parameters in terms of crop germination and growth, including yield. Of course, soil water content is influenced by the occurrence and amount of atmospheric precipitation (e.g. Kovacevic et al., 2007; Maitah et al., 2021; Mohammed et al., 2022; Singh et al., 2024). Atmospheric precipitation reaches the crop, where it is further redistributed. The total amount that reaches the soil can vary considerably depending on the crop. For example, in the case of rainfall in maize (*Zea mays* L.), which is the subject of this paper, Nazari et al. (2020) report values for direct raindrop plus leaf runoff ranging from 31%-83%, stem runoff ranging from 15-25%, and interception ranging from 10-20%. Values of rainfall water reaching the soil are, of course, influenced by total volume, rainfall intensity, row spacing, number of plants per unit area, as well as growth stage and leaf orientation, etc. (Zábransky et al., 2013; Brant et al., 2017; Sun et al., 2017). All of the above aspects affect the resulting soil moisture. In addition to soil moisture, soil temperature is also the subject of the paper, which also affects several parameters (Heinze et al., 2017; Onwuka et al., 2018). In plants, for example, it affects germination, emergence time and the onset of other growth stages (Blacklow, 1972). Its increase can lead to higher total leaf area index (Bollero et al., 1996). For some climatic regions and depending on the time of sowing, an increase in soil temperature is associated with higher maize grain yield and total plant biomass (Vâtcă et al., 2021). Some authors also report on a higher effect of temperature than soil water content on maize emergence (Kurtyka et al., 2011; Gaile 2012; Santos et al., 2018). The layer of organic matter on the soil surface then influences the amount of solar radiation, protects the soil from water loss by evaporation and from erosion, and leads to a reduction in surface runoff or soil temperatures, etc. (Nýč et al., 2015; Hůla et al., 2019; Jaskulski 2019; Kabelka et al., 2021).

The use of different tillage techniques (conventional, strip-till, no-till, etc.) can affect soil water content and soil temperature (and other soil characteristics - physical, chemical and biological), and thus on crop germination and growth (Matus et al., 1997; Torabian et al., 2019; Stipešević and Kladivko 2005; Leskovšek 2021; Faligowska et al., 2022). It has been found that deeper soil loosening can lead to drying and temperature changes (e.g. Gałęzewski et al., 2023). According to various authors, the observed differences in terms of soil water content when comparing conventional tillage and soil conservation techniques may also be influenced by the methods of soil water determination (e.g. Gałęzewski et al., 2023).

In this paper, two basic methods of maize cultivation (conventional cultivation, strip-till) are evaluated. In conventional tillage, the soil surface is usually without post-harvest crop residues (Mhlanga et al., 2016) as they are incorporated into the soil (Kämpf et al., 2016). Strip-till is considered a soil conservation technique (Procházková et al., 2020; Różewicz, M., 2022) and combines the advantages of no-till and conventional tillage, where only part of the soil is tilled, and part remains covered with crop residues. This paper aimed to test the following hypotheses:

1. strip-till will have higher soil moisture at 15 cm soil depth due to higher surface residue coverage;
2. the difference in soil moisture between the techniques will be evident throughout the maize growing season;
3. soil temperature, similar to moisture in strip-till, will be statistically different from conventional cultivation.

MATERIAL AND METHODS

The research was conducted in the Czech Republic in 2023 and 2024 (Figure 1). In 2023, the selected location was in Central Bohemia, and in 2024, the location was in South Bohemia. A more detailed description of the soil parameters at both locations is shown in Table 1.

- Location Central Bohemia – the experimental area is in Central Bohemia. The average annual temperature is 7-8 °C, and the average annual rainfall is approximately 550-650 mm. The altitude of the field is 480-520 meters, and the average slope is 11.6°. Soil type according to WRB (2022) is cambisols.
- Location South Bohemia – the experimental area is in South Bohemia. The average annual temperature is 7-8 °C, and the average annual rainfall is approximately 550-650 mm. The altitude of the field is 440-450 meters, and the average slope is 3.1°. Soil type according to WRB (2022) is stagnosols.

Table 1. Soil conditions at experimental locations

Soil parameter	Central Bohemia	South Bohemia
Texture (USDA*)	Loam	Sandy Loam
pH (KCl)	5.4	5.8
SOC* (%)	0.98	1.16
Bulk density (g/cm^3)	1.44	1.46

*USDA- U.S. Department of Agriculture: texture triangle; SOC-soil organic carbon

In each year, the experimental plots were marked with different variants of maize. All tested variants were located next to each other to ensure the same soil conditions. In total, three sown maize variants were tested in each year and are described below:

- Conventional cultivation: this method is the classical way of cultivating the soil for growing maize. The standard plant spacing for each row is 75 cm. As a rule, tillage is carried out in autumn, supplemented by organic fertilisation. Plant residues are basically absent from the soil surface at the time of sowing.

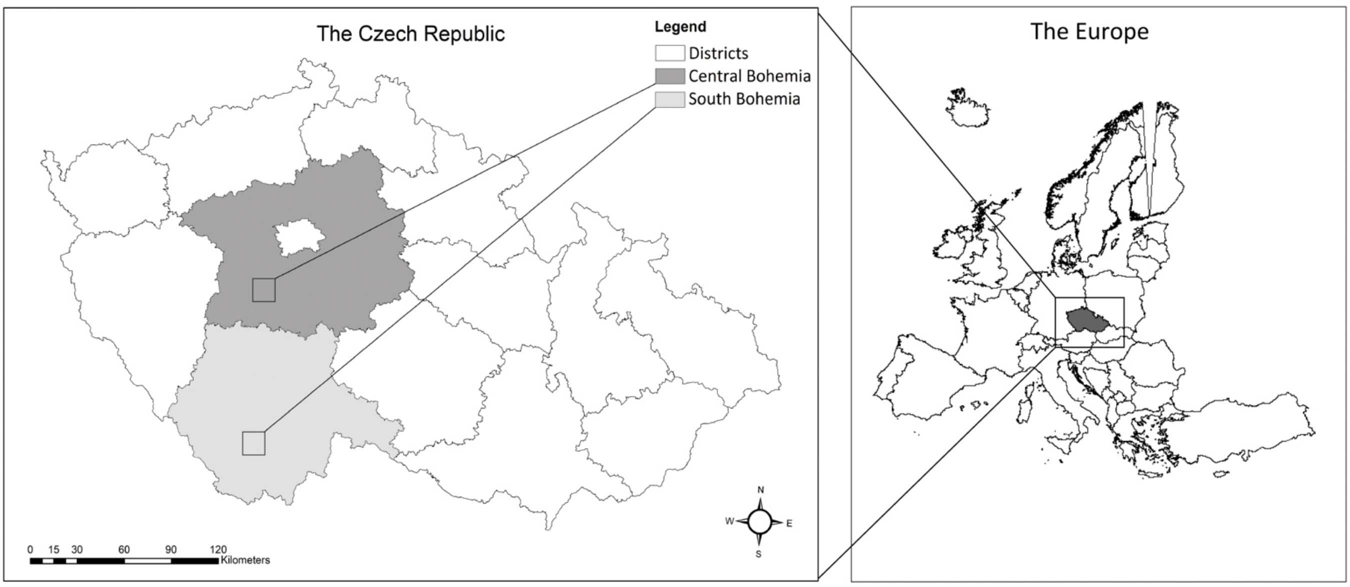

Figure 1. Map of experimental locations in the Czech Republic

– Strip-till: the basic principle is to strip-till the soil in dead plant residues. Only a space of about 25 cm wide is loosened, into which maize is then sown precisely (plant spacing 75 cm). The rest of the surface is not cultivated and is covered with plant residues of different crop species. In both years, two different strip-till variants were tested. In 2023, 1) *Lolium perenne* L., 2) *Trifolium pratense* L. were used for strip-till. In 2024, strip-till was applied to crops of: 1) *Vicia* L. + *Triticosecale* (Witt.) Müntzing, 2) *Secale cereale* L. + *Vicia* L. The strip-till technique is characterized by high surface coverage of plant residues in the spring season.

After marking the experimental plots, the TMS-4 sensors (TOMST, Czech Republic) were set up and checked to avoid possible problems with discharge or lack of memory. This sensor has already been used in a number of papers (Wild et al., 2019; Kopecky et al., 2024; Vopravil et al., 2021; etc.). The TMS-4 dataloggers measure both soil moisture and soil temperature through one moisture sensor and three temperature sensors. Measurements are taken at regular intervals throughout the day. The interval for recording the soil moisture readings was set to every 15 minutes. This was followed by the placement of the sensors in the soil immediately after sowing the maize. The sensors were applied on all three variants in two repetitions to a soil depth of 15 cm. The distance between the two sensors on one variant was 2 meters. In a set interval (15 minutes), the sensors recorded moisture and temperature throughout the maize growing season.

Before the harvest, the TMS-4 sensors were removed from the soil and the data downloaded to the computer, followed by further data processing. There were two TMS-4 sensors per variant. The results from both sensors were averaged so that only one value was worked with. Due to the large number of sensor records, a 3-day interval was chosen for data processing, with the resulting value representing the average moisture content in % (volumetric) for each of the 3 days. Soil temperature, expressed in °C, was processed in the same way.

For data evaluation, the maize growing season was divided into three periods. This step was taken because of the changing parameters on each variant during the season (e.g. residue decomposition in strip-till and the gradual growth of maize plants). The first period represents the period from sowing to approximately one month after sowing. During this period, the maize crops are in the early stages of growth, and the strip-till variants have a significant amount of plant residues on the surface. The second period falls in the growing season from one month after sowing to approximately two months after sowing. The maize has a higher leaf area index, and the plant residues gradually decrease in the strip-till variant. The third period was chosen as two months from sowing to harvest. The maize is fully grown in this period.

The data, divided into three periods, were further statistically evaluated in order to find out the differences between the individual variants. Both soil moisture (%) and temperature (°C) were evaluated. In the case of temperature, the two years (2023, 2024) were additionally compared with each other. For statistical evaluation, the One-Way ANOVA test and Tukey HSD test were chosen at a significance level of P=0.05. This made it possible to determine whether the parameters considered were statistically identical or not.

RESULTS

Soil moisture measured with TMS-4 sensors

Maize: 1st period (from sowing to one month after sowing)

The character of moisture evolution was different in the two evaluated years, as can be clearly seen in Figure 2. The main reason for this is the different climatic conditions due to the air temperature and especially the occurrence of precipitation events in a given year. Precipitation has a major influence on soil moisture. In 2023, precipitation events at the Central Bohemia location were more frequent, which had an impact on soil moisture fluctuations. In 2024 at the South Bohemia location, rainfall was not as frequent and intense. Nevertheless, the same trend was observed at both locations for each technique as described below.

In the first observation period, the average soil moisture values at 15 cm were lowest in the conventional cultivation (see Table 2), which is characterised by low surface cover.

In contrast, the strip-till showed statistically higher moisture content in both years. The main reason for this can be attributed to the surface coverage of plant residues, as these are the basis of this technique. The strip-till was always monitored in two variants (different cover crops). In 2023, there was no statistically significant difference between strip-till (*Trifolium pratense* L.) and strip-till (*Lolium perenne* L.). In 2024, in addition to the statistical difference from the conventional cultivation, there was also a difference between the strip-till variants. The strip-till (*Secale cereale* L. + *Vicia* L.) showed statistically higher moisture content than strip-till (*Vicia* L. + *Triticosecale* (Witt.) Müntzing). The main reason for this was the better quality of the crop residues and the higher surface cover, which was visually evident in the strip-till (vetch+pigeonpea). Hypothesis 1 (higher soil moisture in strip-till) was confirmed in the first period.

Figure 2 also shows that when comparing the differences between conventional cultivation and strip-till, the differences are greatest at the beginning of the period. All lines tend to converge as time progresses. This trend is also clearly visible in Table 2. Throughout the first period, strip-till had a positive effect on soil moisture. Plant residues, by their presence on the surface, prevented evaporation and, at the same time, slowed down surface runoff and promoted water infiltration into the soil when rainfall occurred. This resulted in higher average soil moisture at both locations.

Table 2. Moisture conditions on the tested variants in the first period

Central Bohemia - 2023							South Bohemia - 2024						
Soil moisture (%) - volumetric													
Date	Conventional cultivation		Strip-till: *Trifolium pratense*		Strip-till: *Lolium perenne*		Date	Conventional cultivation		Strip-till: *Vicia + Triticosecale*		Strip-till: *Secale + Vicia*	
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD
27.5	3.69	0.56	15.76	0.49	13.35	0.54	6.6	16.48	0.26	18.15	0.27	20.74	0.29
30.5	3.28	0.51	14.78	0.48	12.38	0.49	9.6	16.68	0.12	18.63	0.17	20.98	0.21
2.6	2.91	0.52	13.80	0.39	11.73	0.46	12.6	16.48	0.17	18.27	0.16	20.37	0.17
5.6	10.73	8.95	18.19	4.76	17.38	6.22	15.6	16.45	0.26	18.08	0.24	19.79	0.23
8.6	16.60	2.86	21.14	0.58	24.35	0.49	18.6	16.61	0.81	18.09	1.08	19.32	0.41
11.6	20.00	4.96	22.46	1.64	25.22	1.07	21.6	17.08	0.11	18.71	0.18	18.96	0.20
14.6	16.24	1.47	20.36	0.66	24.01	0.54	24.6	17.48	0.15	18.90	0.18	19.03	0.20
17.6	18.67	1.44	20.29	0.98	24.22	0.77	27.6	17.20	0.21	18.37	0.19	18.66	0.24
20.6	19.03	3.04	19.81	1.48	23.74	0.99	30.6	16.83	0.11	17.97	0.13	18.33	0.15
23.6	21.31	1.68	24.10	0.78	24.77	0.49	3.7	16.34	0.20	17.49	0.23	17.76	0.30
26.6	18.43	0.77	22.87	1.08	22.53	1.04	6.7	16.18	0.19	17.11	0.16	17.46	0.22
29.6	16.95	0.36	20.10	0.65	19.12	1.03	x	x	x	x	x	x	x
Average	13.99	2.26	19.47	1.17	20.23	1.18	Average	16.71	0.24	18.16	0.27	19.22	0.24

* SD - standard deviation

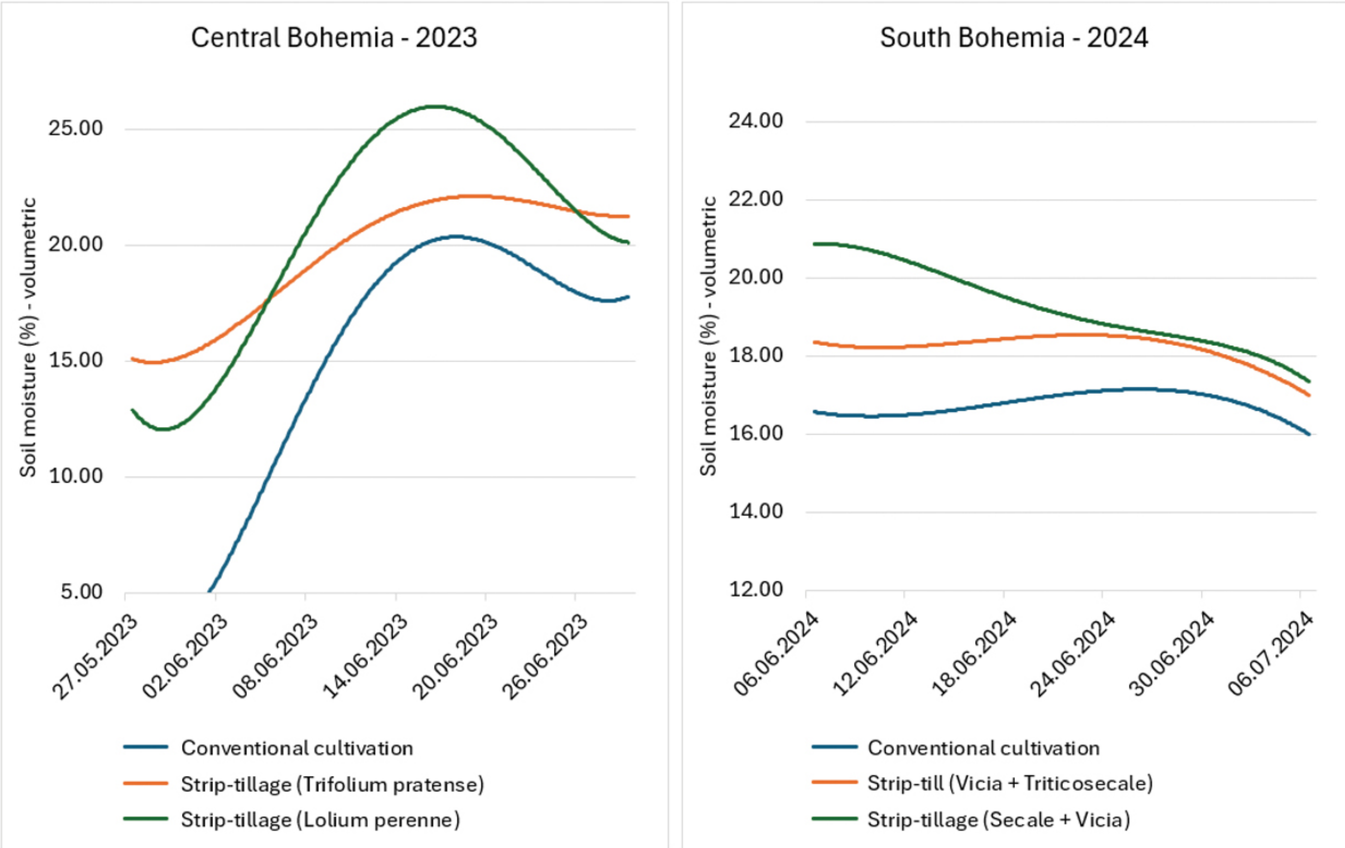

Figure 2. Trend of soil moisture in the experimental plots in the first period (polynomial trend line, fourth degree)

Maize: 2nd period (from the end of the 1st period to two months after sowing)

The beginning of the second period directly follows the end of the first. Again, the lines in the two years under evaluation have a different evolution, which is due, as in the previous case, to the different occurrence and frequency of rainfall. The trend seen in the first period, when the average moisture values were gradually approaching, continued. During the second period, the moisture content of the strip-till was lower than that of the conventional cultivation in a number of cases (Figure 3). This was particularly true for the strip-till (*Lolium perene* L.), where this was also reflected in the statistical evaluation, as this variant is statistically different from the strip-till (*Trifolium pratense* L.). However, the pattern of the trend is the same for both strip-till techniques, as can be clearly seen in Figure 3.

There was no statistical difference between the conventional cultivation and strip-till variants, and therefore, they can be considered identical in the second period (Table 3). One reason for this is the gradual decomposition of the crop residues in strip-till. As a result, the surface cover decreases, and the techniques evaluated gradually become more similar. In addition, conventional cultivation usually leads to partial weeding, which further makes the two farming techniques closer (in terms of surface cover). Another reason is the gradual growth of maize plants. This has the impact of reducing the surface cover effect. While surface cover is a key factor in the period shortly after sowing, once the maize plants are more mature, they are able to intercept any rainfall with their leaves and limit the impact of sunlight. This reduces the effect of remaining crop residues in strip-till techniques.

Table 3. Moisture conditions on the tested variants in the second period

Central Bohemia - 2023							South Bohemia - 2024						
Soil moisture (%) - volumetric													
Date	Conventional cultivation		Strip-till: *Trifolium pratense*		Strip-till: *Lolium perenne*		Date	Conventional cultivation		Strip-till: *Vicia + Triticosecale*		Strip-till: *Secale + Vicia*	
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD
2.7	16.37	0.35	18.55	0.65	16.91	1.05	9.7	16.39	0.82	17.13	0.90	17.47	1.21
5.7	15.69	0.17	16.88	0.50	14.50	0.50	12.7	16.27	0.58	17.19	1.98	17.55	2.22
8.7	15.12	0.41	15.16	0.73	12.40	1.01	15.7	19.21	0.18	22.52	0.18	23.01	0.26
11.7	16.15	4.69	14.62	3.35	10.27	0.66	18.7	18.37	0.76	20.48	0.48	20.04	0.47
14.7	18.43	2.85	20.96	0.71	20.11	4.97	21.7	17.83	0.66	19.71	0.20	19.02	0.92
17.7	18.57	3.52	21.59	2.05	20.82	2.48	24.7	18.14	0.22	19.85	0.19	18.63	0.43
20.7	15.08	0.73	18.87	0.93	17.08	1.34	27.7	17.13	0.25	19.22	0.34	17.11	0.39
23.7	13.57	0.42	16.34	0.79	13.62	1.03	30.7	16.47	0.16	18.41	0.22	16.21	0.18
26.7	12.92	0.14	15.29	0.10	12.53	0.39	2.8	15.60	0.11	17.22	0.07	15.07	0.14
29.7	15.36	2.06	16.19	0.61	12.71	0.33	5.8	15.60	0.14	17.00	0.11	14.97	0.18
1.8	16.30	0.89	16.89	0.23	12.81	0.42	8.8	15.53	0.15	16.82	0.15	14.81	0.18
4.8	15.41	0.47	16.78	0.50	12.41	0.45	x	x	x	x	x	x	x
Average	15.75	1.39	17.34	0.93	14.68	1.22	Average	16.96	0.37	18.69	0.44	17.63	0.60

* SD - standard deviation

Figure 3 shows that when heavier rainfall occurs, strip-till can still slow surface runoff more effectively and promote infiltration of water into the soil. Higher water infiltration results in higher soil moisture. In 2023, this condition is well evident around the time of July 12th, when a higher rainfall event occurred. Shortly after this precipitation event, a significant increase in soil moisture occurred specifically for strip-till, while this increase was less noticeable for conventional cultivation.

A similar situation occurred in 2024, also in the first half of July. The main reason can again be observed in the plant residues on the surface. Although there is a gradual loss of these due to decomposition, they were still present on the soil surface during this period. By the end of the second period, this statement may no longer be true, as there are not many plant residues on the surface. This was confirmed on 26 July 2023, when a more significant rainfall event occurred, and soil moisture in conventional cultivation was higher than strip-till (*Lolium perenne* L.) but lower than strip-till (*Trifolium pratense* L.).

At the end of the second period, in both years, one strip-till technology showed higher average values than conventional cultivation, and the other strip-till technique showed lower values. This is due to the above findings, where both techniques (conventional cultivation, strip-till) become more and more similar as time passes, and different results may occur compared to the first period evaluated. On the basis of the results, hypothesis 2 cannot be confirmed as statistical significance was not confirmed in the second period.

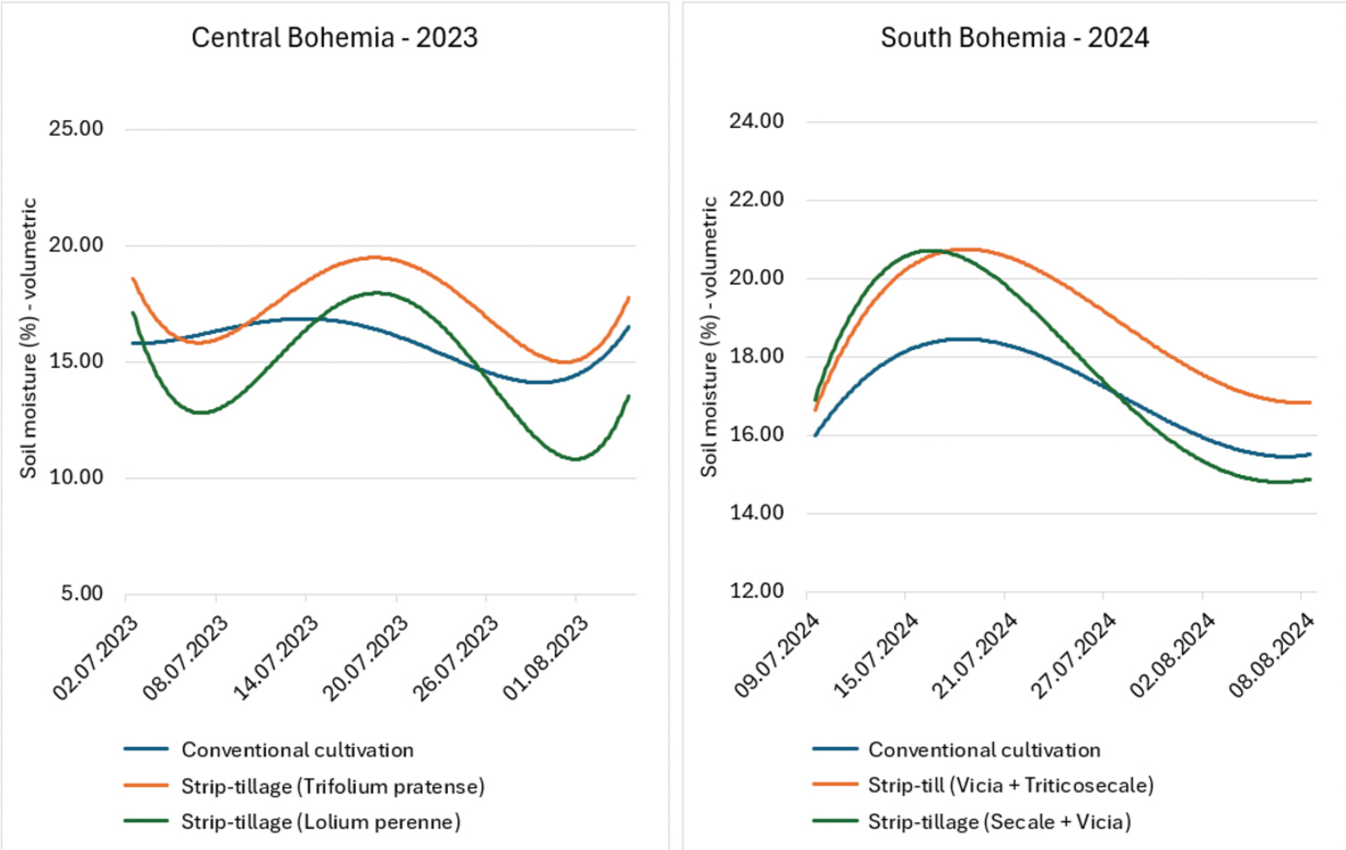

Figure 3. Trend of soil moisture in the experimental plots in the second period (polynomial trend line, fourth degree)

Maize - 3rd season (from the end of the 2nd season to harvest)

The Central Bohemia location received more significant precipitation in 2023 than the South Bohemia location in 2024, where soil moisture trends were downward (Table 4). There were some significant differences in the statistical evaluation (Table 5). In both years, the situation was essentially the same. Conventional cultivation was statistically identical with one strip-till technique each time (*Trifolium pratense* L. 2023; *Secale cereale* L. + *Vicia* L. 2024). A statistically significant difference was found for the other strip-till variant (*Lolium perenne* L. 2023; *Vicia* L. + *Triticosecale* (Witt.) Müntzing 2024). Generalizing the results only to conventional cultivation and strip-till (regardless of cover crop type), it can be concluded that these two techniques are identical during the full growth period of maize. A very important aspect of strip-till in this evaluation is the rate of decomposition of plant residues depending on the type of crop used. Similarly, the effect of weeding must be considered for both conventional cultivation and strip-till. These aspects must be considered individually as they can significantly affect the results in a given year. It may be the case that conventional cultivation achieves better results than strip-till in this period (Figure 4).

Soil temperature from TMS-4 sensors

Soil temperature is generally a more stable parameter. Therefore, one of the aims was to compare whether the soil temperature at 15 cm was statistically the same in both years. The results presented in Figure 5 show the temperature evolution over the growing seasons. Figure 5 shows the temperature changes over the growing seasons. From the results in Table 6, it is clear that the soil temperature trends are statistically significantly different in 2023 and 2024 (P=2.51E-09).

Table 4. Moisture conditions on the tested variants in the third period

	Central Bohemia - 2023							South Bohemia - 2024					
	Soil moisture (%) - volumetric												
Date	Conventional cultivation		Strip-till: *Trifolium pratense*		Strip-till: *Lolium perenne*		Date	Conventional cultivation		Strip-till: *Vicia + Triticosecale*		Strip-till: *Secale + Vicia*	
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD
7.8	22.23	2.69	21.46	1.61	15.11	0.70	11.8	15.54	0.21	16.73	0.30	14.85	0.23
10.8	24.24	2.04	23.40	0.88	16.14	0.43	14.8	15.12	0.14	15.96	0.11	14.45	0.14
13.8	18.44	1.30	22.10	0.43	14.20	0.75	17.8	14.61	0.16	15.21	0.12	14.04	0.15
16.8	14.88	0.61	19.60	0.92	12.08	0.58	20.8	14.70	0.13	15.28	0.11	14.12	0.18
19.8	13.09	0.52	17.06	0.73	10.40	0.54	23.8	14.78	0.16	15.34	0.08	14.29	0.14
22.8	11.87	0.36	15.04	0.57	8.92	0.51	26.8	14.59	0.20	15.11	0.15	14.01	0.26
25.8	11.11	0.26	13.53	0.36	7.62	0.35	29.8	14.74	0.16	15.18	0.11	14.22	0.16
28.8	18.46	6.83	16.84	2.95	9.22	1.68	1.9	14.44	0.17	14.87	0.11	13.94	0.19
31.8	25.13	0.35	21.16	0.26	11.77	0.23	4.9	14.20	0.14	14.68	0.10	13.83	0.17
3.9	23.19	0.73	20.81	0.52	11.30	0.39	7.9	13.86	0.15	14.44	0.06	13.67	0.28
6.9	21.64	0.42	19.61	0.24	10.52	0.41	10.9	13.73	0.16	14.39	0.10	13.83	0.12
Average	18.57	1.46	19.15	0.86	11.57	0.60	Average	14.57	0.16	15.20	0.12	14.11	0.18

* SD - standard deviation

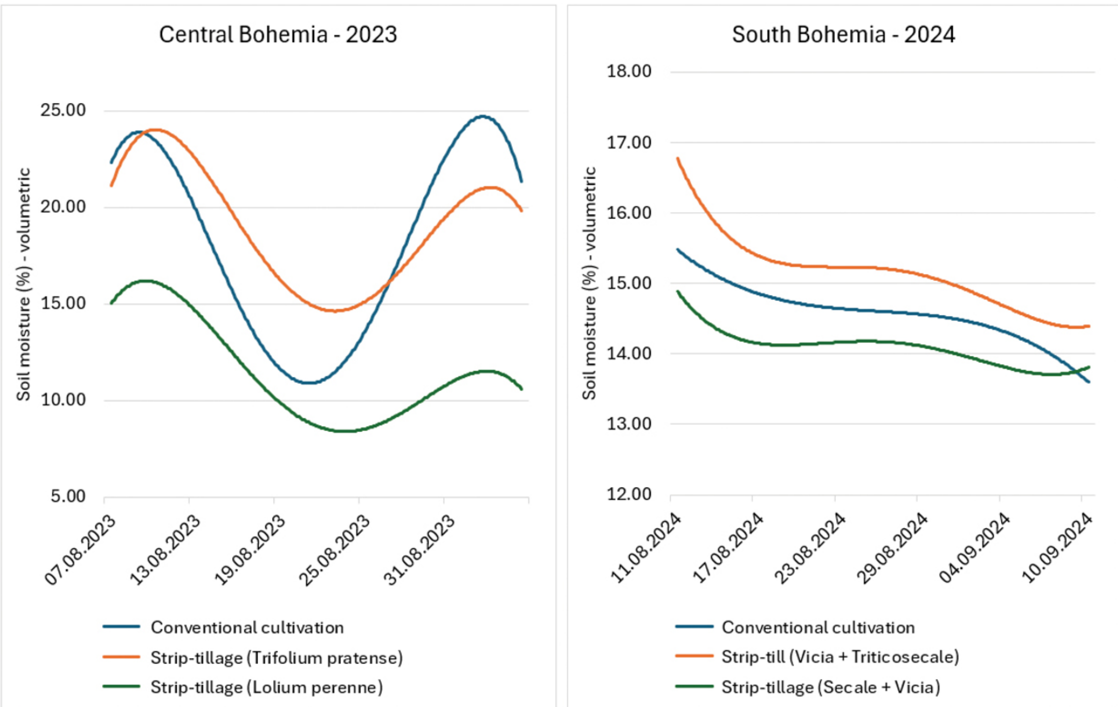

Figure 4. Trend of soil moisture in the experimental plots in the third period (polynomial trend line, fourth degree)

Table 5. Statistical evaluation of soil moisture in each period using One-Way ANOVA and Tukey HSD test (*P*=0.05)

Period	Central Bohemia - 2023			South Bohemia - 2024		
	Variants	One Way Anova	HSD Tukey Test	Variants	One Way Anova	HSD Tukey Test
First	x1-x2	1.43E-02	4.45E-02	x1-x4	8.61E-08	3.46E-04
	x1-x3		1.97E-02	x1-x5		4.84E-08
	x2-x3		9.36E-01	x4-x5		8.45E-03
Second	x1-x2	4.30E-02	2.74E-01	x1-x4	1.23E-01	1.06E-01
	x1-x3		5.53E-01	x1-x5		6.98E-01
	x2-x3		3.47E-02	x4-x5		4.12E-01
Third	x1-x2	6.30E-05	9.33E-01	x1-x4	1.70E-04	2.46E-02
	x1-x3		4.50E-04	x1-x5		1.19E-01
	x2-x3		1.70E-04	x4-x5		1.10E-04

* x1 – conventional cultivation; x2 strip-till (*Trifolium pratense*); x3 strip-till (*Lolium perenne*); x4 – strip-till (*Vicia + Triticosecale*); x5 – strip-till (*Secale + Vicia*)

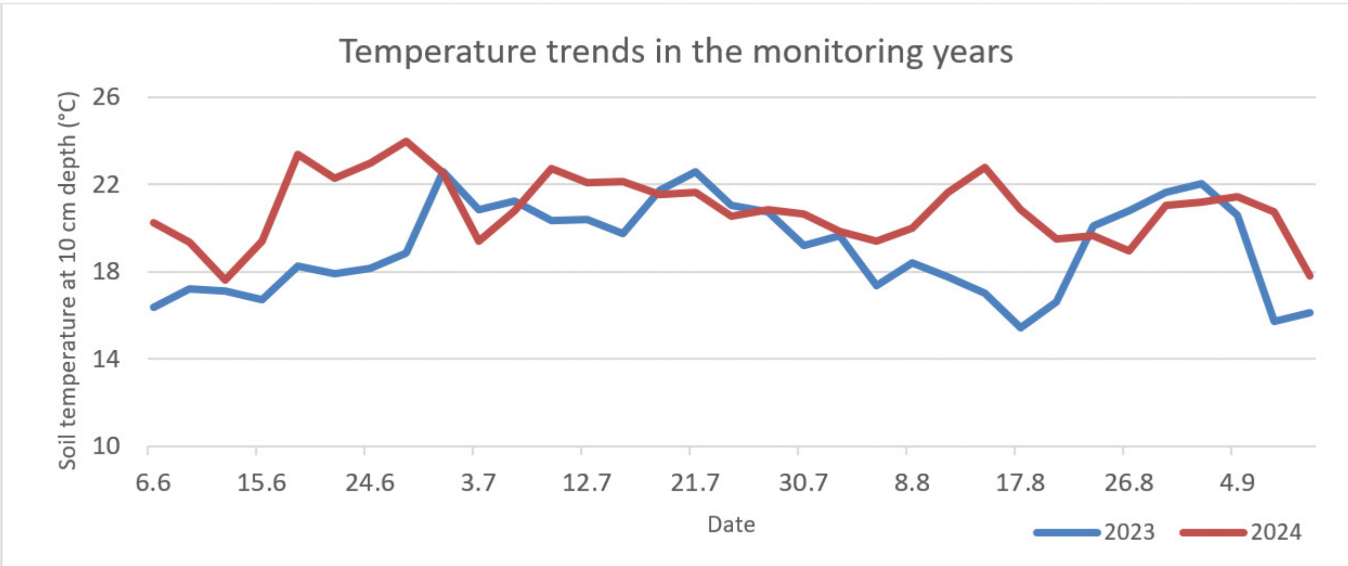

Figure 5. Evolution of soil temperature in the experimental plots in 2023 and 2024

The average soil temperature, regardless of the variant, was 19.19 °C in 2023 and 20.96 °C in 2024. This information is important for the interpretation of the soil moisture results, as two temperature-different years are being compared. Although the soil temperature was statistically different, the trend in soil moisture on the tested variants was essentially maintained in both years. This indicates that soil temperature did not affect the moisture trend.

In addition to the comparison of the two years, the soil temperature was further divided into three periods, as well as the moisture, in order to compare the temperature evolution of conventional cultivation and strip-till. The average results for each variant for the two years evaluated are shown in Table 7, and the statistical evaluation in Table 8. Potentially, the largest difference in soil temperature between the variants should have been in the first period, as was the case for soil moisture.

Table 6. Statistical evaluation of temperature in 2023 and 2024 using One-Way ANOVA and Tukey HSD test (*P*=0.05)

Parameter	2023	2024	One-Way ANOVA (Tukey HSD) *P* = 0.05
Average temperature (°C)	20.96	19.19	2.51E-09
Standard deviation (°C)	1.63	2.21	

Table 7. Average temperature values for each variant in 2023 and 2024

Period	Central Bohemia - 2023						South Bohemia - 2024					
	Temperature in °C											
	Conventional cultivation		Strip-till: *Trifolium pratense*		Strip-till: *Lolium perenne*		Conventional cultivation		Strip-till: *Vicia + Triticosecale*		Strip-till: *Secale + Vicia*	
	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
First	19.5	0.7	18.8	0.6	18.1	0.6	21.0	1.1	21.3	1.0	21.0	0.9
Second	20.3	0.7	19.3	0.6	19.2	0.6	20.9	0.7	20.9	0.6	21.3	0.6
Third	18.5	0.7	18.0	0.7	18.2	0.7	20.4	0.6	20.1	0.6	21.1	0.7

* SD - standard deviation

Table 8. Statistical evaluation of temperature at 3-day intervals in each period using One-Way ANOVA and Tukey HSD test (*P*=0.05)

Period	Central Bohemia - 2023			South Bohemia - 2024		
	Variants	One Way Anova	HSD Tukey Test	Variants	One Way Anova	HSD Tukey Test
First	x1-x2	2.81E-01	6.74E-01	x1-x4	8.96E-01	9.15E-01
	x1-x3		2.50E-01	x1-x5		1.00E+00
	x2-x3		7.23E-01	x4-x5		9.11E-01
Second	x1-x2	2.65E-01	3.78E-01	x1-x4	5.71E-01	9.90E-01
	x1-x3		2.96E-01	x1-x5		6.76E-01
	x2-x3		9.85E-01	x4-x5		5.91E-01
Third	x1-x2	2.65E-01	3.78E-01	x1-x4	5.71E-01	9.90E-01
	x1-x3		2.96E-01	x1-x5		6.76E-01
	x2-x3		9.85E-01	x4-x5		5.91E-01

* x1 – conventional cultivation; x2 strip-till (*Trifolium pratense*); x3 strip-till (*Lolium perenne*); x4 – strip-till (*Vicia + Triticosecale*); x5 – strip-till (*Secale + Vicia*)

This was partially fulfilled in 2023, when the average temperature was higher in the first period for conventional cultivation (Table 7). However, the differences between the variants were very small and, when the standard deviation was considered, there was an overlap of values, which had a major impact on the statistical evaluation, in which no statistical difference was confirmed. In 2024, the results for all variants show very similar values in all three periods. It is important to mention here again that this is the temperature at a depth of 15 cm, as some differences could be expected in the case of surface measurements due to the presence of plant residues. However, at 15 cm depth, their effect was not apparent, which means that hypothesis 3 was not confirmed

DISCUSSION

Copec et al. (2015) studied the effect of different tillage methods (conventional cultivation, conservation tillage, no-till) on soil water content and yields in maize and wheat cultivation in Croatia. For example, the authors report the highest soil water content during maize cultivation in the no-till variant at a depth of up to 20 cm (increased infiltration and reduced evaporation); the least soil water was found in conventional cultivation. The absence of tillage can lead to lower or higher crop yields (or no effect on yields) compared to conventional cultivation. For maize, Copec et al. (2015) report lower yields for the no-till compared to conventional cultivation, but only in some years. In contrast, Sun et al. (2024) report in an extensive review that yields can be comparable in some cases for conventional cultivation and soil conservation techniques. Wang et al. (2024) studied the effect of different strip-till strip widths when it is used in maize cultivation on the water content (and temperature) of the soil layer up to 20 cm soil depth (and other soil properties). The authors report the differences in water content (and changes in soil water content during and after rainfall) between the variants with different strip-tilled strip widths. Licht and Al-Kaisi (2005) studied the effect of tillage methods, namely conventional, strip-till and no-till, on the soil temperature pattern during selected days characterized by different weather conditions and soil volumetric moisture content. These authors reported that soil volumetric moisture at depths up to 120 cm was maximum for no-till and strip-till, but that the differences between the technologies studied were small.

Gałęzewski et al. (2023) also studied soil water content and soil temperature (at a depth of 5 to 15 cm) under conventional cultivation versus strip-till in winter barley. The authors reported higher soil water content for the strip-till only during part of the growing season (BBCH 87 versus BBCH 77); for both variants, soil water content was higher between rows compared to within rows. Jaskulski (2019) studied changes in soil water content when winter wheat, winter canola, and maize were grown using strip-till. The authors reported that during wheat cultivation, soil water content was higher between rows than in rows in the absence of rain for at least 14 days or at least 5 days after rain; in contrast, just after rain, soil water content was higher in rows.

For soil temperature monitoring, Wang et al. (2024), in their study on different strip widths for strip-till (maize), report differences between the variants with different strip widths treated to a depth of 20 cm (including the amplitude of daily soil temperature fluctuations and the time of occurrence of maximum and minimum temperatures) determined directly in and outside the cultivated strips. For soil temperature, they report the maximum differences between the variants during the first weeks after sowing, whereas before harvest, these differences were small.

However, Wang et al. (2024) assume that given soil temperature (or soil water content) results may not be evident under other climatic conditions. Gałęzewski et al. (2023) state lower temperatures (and amplitude of temperature fluctuations) in the case of strip-till in winter barley cultivation by an average of 0.64 °C (for both row and inter-row) for almost the entire growing season. Compared to conventional cultivation, strip-till heated and cooled the soil more slowly due to its higher water content. For conventional cultivation, soil temperature was slightly higher in the rows compared to between rows (and for strip-till, soil temperature was slightly higher between rows). Licht and Al-Kaisi (2005) reported the highest soil temperatures in the top 5 cm of soil for the conventional cultivation and the lowest for the no-till (comparing conventional cultivation, strip-till, and no-till - for maize); however, there were noticeable differences between techniques as the day progressed (and as weather conditions changed - clear sky, cloudy, rain).

CONCLUSION

Sufficient water in the soil is essential for plant growth. The results show that the strip-till technique contributes to a higher infiltration of water into the soil shortly after sowing of maize due to the higher surface roughness, and therefore to a higher moisture content. This is one of the reasons why strip-till is considered a highly effective soil conservation technique. In this context, the quality and type of crop residues in strip-till are very important, as this tends to influence the results considerably. Nevertheless, in all cases, a significantly higher soil moisture was confirmed in the first period (from sowing to one month after sowing), regardless of the quality of the crop in strip-till. The effect of plant residues on the soil surface decreases with time in strip-till. More than one month after sowing, the higher soil moisture may no longer be noticeable with this technique, as confirmed by the measured results. Due to the decomposition of crop residues and the growth of maize, the differences between the evaluated variants decreased. From the second period between the conventional cultivation and the strip-till, there was no longer a statistically significant difference in soil moisture at a depth of 15 cm.

In terms of temperature, the years evaluated were statistically different, but the effect of plant residues on soil moisture was maintained in the first period. No statistically significant differences were detected in the evaluation of temperature for the individual variants, which confirmed the fact that it is a more stable soil parameter than soil moisture, where more significant fluctuations were observed.

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4.2 Chmel otáčivý (*Humulus lupulus* L.)

Chmel otáčivý je víceletá (vytrvalá) rostlina s důležitým hospodářským významem pro pivovarnictví, ale i pro další potravinářské a jiné sektory. V České republice má pěstování chmele dlouholetou tradici. České chmelové odrůdy (žatecký poloraný červeňák, sládek aj.) jsou celosvětově uznávány pro svou vysokou kvalitu šištic. Z hlediska pěstitelských nároků vyžaduje chmel úrodné a hluboké půdy s dostatkem organické hmoty a příznivým vodním režimem.

Ve chmelnicích a obecně ve vytrvalých kulturách není v současné době kladen přílišný důraz na ochranu půdy před její degradace vodní erozí. Přitom řada pozemků se nachází ve svažitém terénu. Vytrvalé kultury se navíc vyznačují vysoce intenzivním obděláváním, během kterého půda podléhá dalším degradačním procesům (zhutnění půdy v prostoru kolejových stop, ztráta organické hmoty apod.).

V případě chmelnic je při klasickém způsobu obhospodařování snaha udržovat meziřadí v průběhu roku bez rostlinného pokryvu. Několikrát do roka se provádí mělké kypření s cílem omezit plevele, podpořit infiltraci vody či připravit půdu pro přiorávku chmelových řadů. Tento způsob hospodaření se v době klimatické změny jeví z pohledu ochrany půdy před vodní erozí jako nedostatečný. Při překročení infiltrační schopnosti půdy může mít navíc mělké kypření negativní efekt a způsobit tak výrazný smyv půdy v důsledku nakypřené svrchní vrstvy.

Cílem by proto měl být technologický způsob hospodaření, který jednak zajistí dostatečnou ochranu půdy svažitých pozemků a zároveň nebude mít negativní dopady na výslednou produkci chmele. Rovněž by řešení nemělo nadměrně zasahovat do zaběhnutých způsobů hospodaření. Možnosti protierozní ochrany ve chmelnicích jsou proto značně omezené. Pokud se odpoutáme od skutečnosti, že nové chmelnice se nedoporučuje zakládat na erozně ohrožených plochách, je potřeba mít k dispozici vhodnou ochranu pro chmelnice stávající. Vzhledem k tomu, že je na pozemku přítomna chmelová konstrukce, není možné aplikovat organizační ani technická protierozní opatření. Zbývající možností je úprava agrotechnických postupů. Jako vhodné řešení se ukazuje ozeleněné meziřadí pomocí vhodných druhů meziplodin. Mezipolodiny zvyšují pokryvnost povrchu půdy a tím snižují rozsah vodní eroze. Kromě protierozní účinnosti má ozeleněné meziřadí celou řadu dalších pozitivních aspektů.

Protierozní účinnost u ozeleněného meziřadí je podrobně popsána v následujících třech publikacích (3, 4 a 5). **Publikace 3** je zaměřena na porovnání protierozní účinnosti konvenčního způsobu hospodaření s technologií osetého meziřadí. Posuzována je doba krátce po setí, až do plného zapojení zasetých meziplodin. Na **Publikaci 3** navazuje **Publikace 4** věnující se vyplavování organické hmoty z půdy vlivem vodní eroze. Celou problematiku doplňuje **Publikace 5**. Ta je zaměřena na tzv. soil loss ratio (SLT) udávající průměrnou ztrátu půdy v přesně definovaných obdobích u daného technologického postupu. Z SLT je v **Publikaci 5** dále spočítán ochranný vliv vegetace (C-faktor). C-faktor představuje parametr, který je součástí rovnice USLE (Universal Soil Loss Equation) využívané pro výpočet dlouhodobé ztráty půdy.

Publikace 3

Název

Impact of cover crops in inter-rows of hop gardens on reducing soil loss due to water erosion.

Citace

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Impact of cover crops in inter-rows of hop gardens on reducing soil loss due to water erosion

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Abstract: Soil degradation caused by water erosion in sloping hop gardens is definitely a serious issue because the space in inter-rows is without plant residues for most of the year in traditional cultivation. Cover crops in inter-rows of hop gardens and their efficiency in soil conservation are assessed in this article. There is only little research available in this area, and our data bring unique information on water erosion in hop gardens. Technologies with different types of cover crops were always compared with the conventional cultivation. The research was conducted within the years 2016–2020. A field rainfall simulator was used to determine the soil conservation effectiveness of selected technologies. The simulated rainfall was performed in two stages of cover crops growth with the main aim to measure the overall soil loss. The outcomes from the measurements confirmed that cover crops in inter-rows of hop gardens protect the soil surface from falling raindrops and significantly (P-value < 0.05) reduce soil loss. It can be concluded that this technology had a soil conservation effect already one month after sowing, and it is a basis for sustainable agricultural management on sloping hop gardens.

Keywords: extreme precipitation; sloping land; *Humulus lupulus* L.; permanent crops

On sloping lands, water erosion is the main factor of soil degradation and causes irreversible changes (Gao et al. 2011). Unfortunately, the problem of soil water erosion on agricultural land has been an inseparable part of the environmental threats in the last decades (Lal 1994). It negatively influences food production, drinking water quality, ecosystem services, eutrophication, mud floods, biodiversity or carbon stock in soil (Boardman and Poesen 2006). Moreover, under climate change, the frequency of extreme rainfall is expected to increase (Groisman et al. 2005, Eekhout et al. 2018), which is likely to exacerbate the problem of water erosion. It means that more agricultural lands located in a slope will require erosion control measures (Li and Fang 2016). One of the most problematic agricultural crops from the soil erosion point of view is hop (*Humulus lupulus* L.). Hop gardens are highly prone to water erosion in the traditional way of cultivation (Kabelka et al. 2019). The plants have a well-developed root system (Brant et al. 2020), but they are planted in construction with wide rows and the inter-rows of the hop garden are not protected against water erosion (Auerswald et al. 2009). In the case of sloping land, there is strong soil loss in every heavy rain (Bagio et al. 2017). Finding some information in the scientific literature about an effective soil conservation technology for hop gardens is quite problematic; however, it is possible to look at the research of other permanent crops where the situation is better. For example, several studies (Marques et al. 2010, Palese et al. 2014, Biddoccu et al. 2017) report that cover crops (or grass cover) in the inter-rows are suitable as a soil management practice adopted to reduce surface runoff and soil erosion in vineyards or orchards. Cover crops are meant to be suitable for plant species (e.g.,

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Secale cereale L., *Phacelia tanacetifolia* Benth., *Vicia sativa* L., *Sinapis alba* L., etc.) that are cultivated in the inter-rows (Krofta et al. 2012). It supposes that the cover crops growing in inter-rows of sloping hop gardens reduce soil loss and surface runoff. However, the information on effectiveness is lacking. The main aim of this article is, therefore, to quantify the soil loss in conventional cultivation (CC) technology and in soil conservation technology (SCT) with different types of cover crops in inter-rows of hop gardens.

MATERIAL AND METHODS

The research took place in hop gardens near the Solopysky village and was conducted within the years 2016–2020. This is a typical hop-growing area in the Czech Republic with a slightly warm to dry climate. The mean annual temperature is 7–8.5 °C, and rainfall is 450–550 mm. Soils in experimental plots were determined as Luvic Cambisols. The basic properties of soils are listed in Table 1. Experimental plots had the length of at least 16 meters (two-column fields) and the slope was 17% (year 2016–2018, GPS: 50.2592208N, 13.7413078E) and 9% (year 2019–2020, GPS: 50.2553675N, 13.7355892E).

In total, 4 technologies were selected to verify and check the soil loss. CC was selected as the control technology, and the three remaining SCT variants were always established in early April. All verified technologies are mentioned in the following text:

(a) conventional cultivation (CC);
(b) *Phacelia tanacetifolia* Benth. (SCT);
(c) grass-legume mixture (SCT);
(d) *Sinapis alba* L. (SCT).

A rainfall simulator with four nozzles was used to measure water erosion. It is a widespread device in the research of soil erosion processes (Chmelová and Šarapatka 2002, Lassu et al. 2015, Kabelka et al. 2020). A total of 76 rainfall simulations were performed. The principle of measuring by rainfall simulator is based on spraying water on a clearly defined area. In our case, the size of the rainfall simulation area is 21 m^2.

Table 1. The basic properties of soils in experimental plots

Soil texture (%)				C_{ox}	N_{tot}	C/N
< 0.002	< 0.01	< 0.05	< 0.1	(%)		
23.8	36.5	66.7	84.4	1.53	0.184	8.3

C_{ox} – oxidisable carbon; N_{tot} – total nitrogen

Table 2. The average distribution of R factor into months in the Czech Republic (Janeček et al. 2012)

	IV	V	VI	VII	VIII	IX	X
Factor R (%)	1	11	22	30	26	8	2

At the bottom part of the defined area, there is a water-collecting flume through which the surface runoff flows together with the eroded soil particles. Rainfall simulator allows monitoring soil loss, the amount of precipitation, water infiltration or the beginning and the end of surface runoff. Therefore, the outcomes from the rainfall simulator offer a complex set of information on verified technologies and their soil conservation effectiveness during the simulations. It is important to ensure soil and slope conditions of individual experimental plots to be as similar as possible.

Rainfall simulations on the designated area were always done twice consecutively. The length of the first rainfall simulation was 30-min. This was followed by a 15-min technological break. After that, there was the second rainfall simulation with a duration of 15 min. Two rainfall simulations were performed in order to verify the conditions of the soil with natural moisture and subsequently the conditions of the soil already saturated. Verification of selected technologies took place in two development stages of cover crops in growing terms stated in the guidelines "Predicting rainfall erosion losses – a guide to conservation planning" (Wischmeier and Smith 1978). The description of individual growing terms is stated below:

– First-term of rainfall simulations (second growing period) – the period from plot preparation to sowing up to one month after sowing or planting.
– The second term of rainfall simulations (third growing period) – the period of the second month from spring or summer sowing.

These terms correspond to the end of April (Ist term) and the end of June (IInd term). In this period, torrential rains already occur in the Czech Republic. Their distribution within individual months is shown in Table 2.

The rainfall intensity was set to be 1 mm/min. To determine the rate of soil loss, the samples of surface runoff with eroded sediments were taken every three minutes from the water-collecting flume on the place of outflow surface runoff from the simulated area. After rainfall simulation, each sample was dried in the oven for 12 h at 105 °C in the laboratory. This

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determined the weight of eroded particles (mg) for each sample. Based on the amount of eroded particles and the amount of surface runoff, the total soil loss in individual technologies was calculated. Each term of measurement and each technology (CC, SCT) was examined for normal distribution using the Shapiro-Wilk test (P-value < 0.05). In some cases, the values did not have a normal distribution, so it was decided to demonstrate the difference between technologies using the non-parametric Mann-Whitney U-test (P-value < 0.05).

RESULTS AND DISCUSSION

Results of the five-year research show that the worst technology is CC, as supposed, which was chosen as the control technology, and the SCT results were related to it. The information on soil conservation efficiency is quite unique because a considerable part of studies devoted to hop gardens is focused on hop breeding (Patzak et al. 2010), protection against harmful organisms (Bedini et al. 2015) or qualitative parameters of hops (Almaguer et al. 2014). However, there are very few research studies evaluating the soil degradation caused by water erosion in hop gardens in case they are located on slope areas. The results of CC confirm insufficient soil conservation efficiency of traditional hop gardens cultivation. On the other hand, the importance of cover crops is apparent.

The most prone period is the time shortly after cover crops sowing (Nunes et al. 2011). Nevertheless, the results in Figure 1 show a positive soil conservation effect even in their first growing stage. The highest soil losses were mostly measured in technology with *Sinapis alba*, but the positive trend is still apparent in this technology. In this article, cover crops are evaluated regardless of the crop type.

In the first term of measurement (the month after sowing), the significant (P-value < 0.05) soil conservation efficiency of cover crops was determined in rainfall simulation on naturally moist soils. The soil loss in SCT was lower by 54.9% (Figure 2) compared to CC. The initial soil moisture varied slightly from year to year. However, the most important factor is that the rainfall simulations between verified technologies in individual terms were performed in a minimum time span (usually within a day). The aim was to ensure equivalent conditions during the simulations. After the first simulation, the soil moisture conditions in the verified technologies can be considered as unified. In the second rainfall simulations on saturated soils, the differences in the soil loss decreased in all the verified SCT technologies compared to rainfall simulations on naturally moist soils. The main reasons are soil saturation from the previous rainfall simulation and the small height of plants in the first month after sowing. This meant that the soil conservation effect was not statistically confirmed.

Cover crops' soil conservation efficiency increased during the season up to their full growth (Figure 2). The maximum soil conservation effect was measured during the second term of measurement (two months after sowing), which corresponds to the end of May

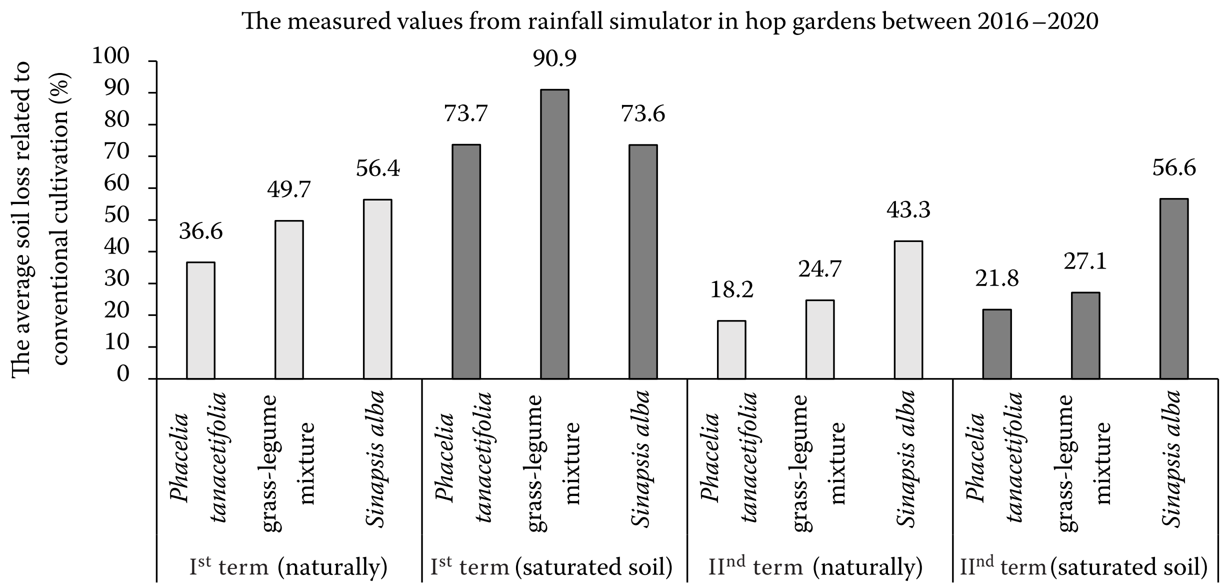

Figure 1. The average efficiency of the individual cover crops in inter-rows of hop gardens

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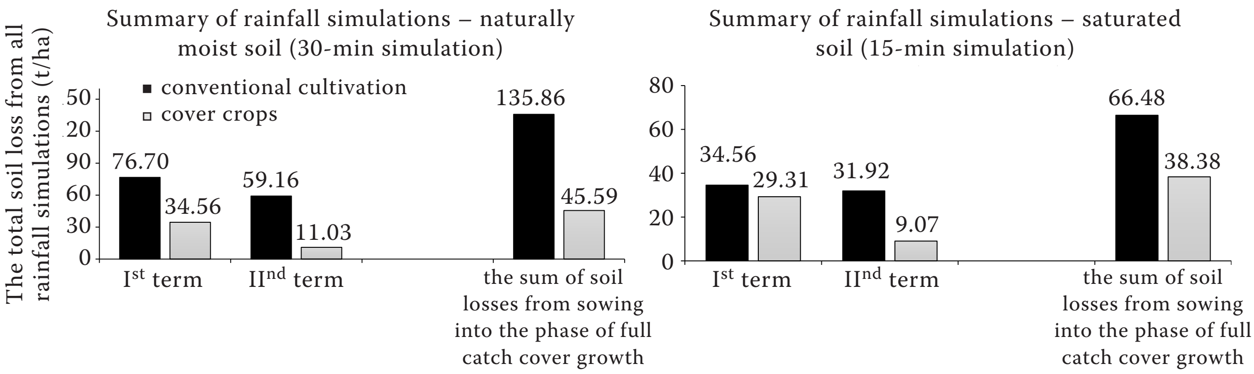

Figure 2. Overall results from all rainfall simulations in 2016–2020

when the cover crops were fully grown. A considerable influence of SCT on reducing soil loss was clearly apparent in rainfall simulations on naturally moist soils (lower soil loss by 81.4%). Due to the fact that the plants were already fully grown, a significant soil conservation effect was also measured in the rainfall simulation on saturated soils (lower soil loss by 71.6%). The outcomes from both rainfall simulations were confirmed by statistical tests (P-value < 0.05). The statistical indicators from our research are depicted in Table 3.

Based on our data measured in the SCT, a prediction model was determined, which shows the effectiveness of soil conservation (space between the lines) from the time of sowing for two months (Figure 3). The results indicate that if the cover crops are sown in early April, they can prevent hop gardens from the soil loss during the periods of the frequent occurrence of torrential rains. After the phase of full growth, the cover crops begin gradually dry up and generally, their leaf area index is decreasing (Reichenau et al. 2016). However, due to the fact that they are still present in inter-rows until the hops harvest, their soil conservation effect in this period is also assumed.

Of course, using cover crops is not without flaws. Track trajectories cause the biggest issues. In these places, there are traces of soil compaction, and surface runoff usually starts in these places. However, as reported by Smirnov et al. (2019), the problem of soil compaction in the track trajectories also occurs

Table 3. The statistical evaluation of soil loss from rainfall simulations 2016–2020

	Ist term		IInd term	
	CC	SCT	CC	SCT
The soil loss – naturally moist soil				
Mean (t/ha)	15.34	6.8605	11.832	2.206
Median (t/ha)	15.27	8.11	7.73	2.245
Counts	5	5	5	5
Mann-Whitney U test	hypotheses H1 group 1 > group 2			
P-value	0.048		> 0.01	
The soil loss – saturated soil				
Mean (t/ha)	6.912	5.862	6.384	1.813
Median (t/ha)	6.57	5.495	6.48	1.14
Counts	5	5	5	5
Mann-Whitney U test	hypotheses H1 group 1 > group 2			
P-value	0.345		> 0.01	

CC – conventional cultivation; SCT – technology with cover crops; CC was measured once a year for five years. Hence 5 is the number of counts; in 2016 there were 4 SCT measurements in each term, in 2017–2020 there were 2 SCT measurements in each term. The mean in both terms (Ist and IInd term) was calculated from the measured data every year. Therefore, the number of counts is also 5

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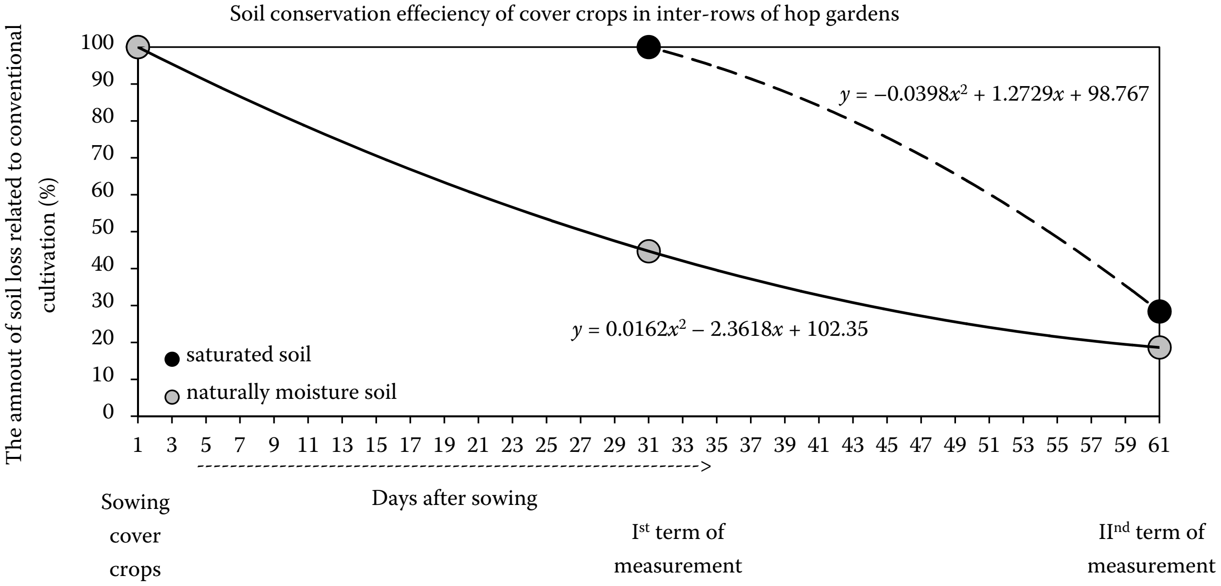

Figure 3. Prediction of soil loss in two months after sowing. The value of saturated soil in the I[st] term of measurement is 100% because the results of soil conservation technology were not statistically different from the results of conventional cultivation

in CC. It is, unfortunately, an inseparable part of hop gardens cultivating due to frequent traffic of agricultural machinery. Another problem can be weeds, which are often considered a serious threat in agriculture (Clark et al. 1998). On the other hand, some authors (Yagioka et al. 2015, Hashimi et al. 2019) state that weeds can have a similar function as cover crops. Weeds also cover the soil, so it might be possible to reduce water erosion in this way, but it is necessary to perform mulching before their reproduction in inter-rows for weeds control (Gupta 1991). Plant residues from mulching then further protect the soil from water erosion (Meyer et al. 1970).

Some comparisons of our results can be made with the research conducted in other permanent crops (vineyards, orchards), where it is possible to find out more information on water erosion. Novara et al. (2011) measured lower soil loss for SCT by up to 76% compared to CC in vineyards. In a similar way, Marques et al. (2010) state 84.6% lower soil loss in SCT. Biddocu et al. (2017) also do not differ much in the results for vineyards (lower soil loss by 72% to 89%). In orchards, Gómez et al. (2009) determined lower soil loss in SCT by 79% compared to CC. All these studies are in line with our results measured for hop gardens. Blanco and Lal (2010) state that the main cause of water erosion on sloping plots is insufficient soil cover. The conclusion of this article is the same. When the cover crops are in inter-rows, the consequences of water erosion are much lower compared to CC without vegetation. Due to the positive results in SCT, it can be concluded that cover crops in inter-rows of sloping hop gardens significantly reduce soil loss.

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Publikace 4

Název

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Reduction in soil organic matter loss caused by water erosion in inter-rows of hop gardens

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Abstract: Currently, when cultivating *Humulus lupulus*, there is no systematic farming reducing soil erosion in the Czech Republic. As a result, annual irreversible soil and organic matter losses due to intensive rains occur on soils of hop gardens threatened by erosion. One of the possibilities how to reduce water erosion in hop gardens and thereby to decrease the amount of washed away organic matter is using the conservation effect of suitably selected catch crops in inter-rows. Two catch crops were selected to test: *Phacelia tanacetifolia* and a grass-legume mixture. Organic matter in soil is a key factor to maintain the stable soil environment and our results show that the amount of washed away organic matter was reduced by more than half compared to conventional farming (60% – naturally moist soil, 54.5% – soil already saturated). The research was conducted between the years 2016 and 2017 close to the village of Solopysky. Soil loss was investigated using a rainfall simulator from which the organic matter washing away was consequently determined. The rainfall simulator is a device enabling to measure not only the soil loss due to water erosion but also the volume of surface runoff, infiltration etc. From the outcomes of measurements carried out with rainfall simulator it is apparent that these technologies have a significant soil conservation potential in hop gardens.

Keywords: catch crops; permanent crops; soil conservation technologies; soil degradation

Soil water erosion is the process by which soil material (either organic or inorganic) is removed from its initial place by a combined action of raindrop energy and runoff (Goebel *et al*. 2005). It is one of the principal mechanisms of land degradation (Lal 2003; Bationo *et al*. 2007) and very serious worldwide issues. In the Czech Republic more than 51% of agricultural land is threatened by soil degradation (Šarapatka & Bednář 2015). It is vital to realize that one centimetre of soil takes decades up to hundred years to form and the consequent renewal of degraded soil is a very lengthy and expensive process and in many cases the remedy-renewal process is not even possible (Randolph 2004). If the soil is to fulfil all its functions, its fundamental properties cannot be principally affected. For more than a century, soil organic matter has been recognized as a key determinant of soil fertility and

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agricultural production (Hilgard 1906; Tiessen *et al*. 1994; Bordonal *et al*. 2017). Due to an optimum amount of good-quality organic matter in soils, the soil is able to fulfil a range of irreplaceable processes which have a significant influence on physical and chemical soil properties (Reicosky 2003) and play a critical role in sustaining soil quality and sustainable agricultural productivity (Amundson *et al*. 2015). Organic matter undergoes transformations in soil, such as mineralization, humification, assimilation or stabilisation (Guggenberger 2005). Humification has the most significant effect on soil fertility (Pettit 2004). Humus also contains substances which can affect plants as hormonal stimulators. Even a small amount of humus can significantly improve the soil ability instrumental in plant growth (Brady & Weil 2002).

Organic matter loss in soils is generally regarded as the most significant factor of soil degradation process. Numerous studies have demonstrated that soil erosion has significant negative impacts on the organic matter and nutrients in soils and sediments (Gregorich *et al*. 1998; Fu *et al*. 2009; Kirkels *et al*. 2014). The loss is caused predominantly by wind and water erosion and by insufficient supply of organic fertilisers into soils (Ritter & Eng 2012). Soil particles are taken by erosion along with the fine humified part of soils, which is the most precious part of soil profile and its lack significantly influences the scope and speed of degradation processes. These processes have strong impacts on soil organic carbon dynamics in soil (Lal 2005; Xiao *et al*. 2017)

Water erosion is particularly manifested on sloping plots of land in crops insufficiently covering the soil surface. One of the crops which significantly contribute to water erosion and consequently to organic matter loss is hop. The hop is a permanent crop remaining on one plot for 20 to 25 years, sometimes even longer (Štranc *et al*. 2012). All over the world the hop is cultivated in row spacing from 2.7 to 4.2 m and if the hop garden is located on a hillslope and the soil conservation in inter-rows is not sufficient, it is easily prone to water erosion. These hop gardens lose their most fertile part when torrential rains occur.

One solution could be using catch crops intended for green manure (Duran-Zuazo & Rodriguez-Plequezuelo 2008; Marques *et al*. 2016). Catch crops are thought to be suitable underplanted crops cultivated in inter-rows of hop gardens (Krofta *et al*. 2012). Catch crops have long been valued for their soil conservation benefits (Kaspar & Singer 2011; Chatterjee 2013) including reduction in runoff and soil erosion (Gómez *et al*. 2009; Jahanzad *et al*. 2017; Etemadi *et al*. 2018), improvement of soil structure (Palese *et al*. 2014) and increase in infiltration and soil organic carbon content (Vanderlinden *et al*. 1998; Marquez-Garcia *et al*. 2013). Catch crops can also be a promising option to accelerate carbon sequestration (Paustian *et al*. 2016; Pardo *et al*. 2017). A suitable combination of catch crops has a positive effect on soil structures also due to underground biomass. Underground biomass is understood as the root system of crops. Roots are one of the main sources of carbon and nitrogen in soils (Zdruli *et al*. 2004; Rasse *et al*. 2005); their labile carbon compounds and root exudates contribute to the stabilization of soil in the upper 5-cm layer (Jackson *et al*. 2017).

MATERIAL AND METHODS

The research was conducted near the village of Solopysky, which is located 12 km south-west of the town of Louny. Typical climate is slightly warm and dry. Mean annual rainfall is 450–550 mm and temperature 7–8.5°C. The terrain of wider surroundings is significantly rugged. Soils are luvic Cambisols due to texture differentiation. In irregular locations there are fluvic characters (IUSS Working Group 2015). The main soil-forming process is weathering permacarbon with neutral or weak alkaline reaction. The basic soil properties: 1.53% total oxidizable carbon (Cox); humus 2.64%; total nitrogen (Ntot) 0.184; C/N ratio 8.3. The topsoil layer up to 50 cm (the soil texture: < 0.002 mm – 23.8%; < 0.01 mm 36.5%; < 0.05 mm – 66.7%; < 0.1 mm – 84.4%). There are mentions of soil compaction in wheel tracks. These tracks are unfortunately an inseparable part of hop gardens due to the frequent traffic of agricultural machinery.

Plots for tested technologies were selected particularly for their height and uniform slope, which exceeded 17% in some parts. Soil conservation effectiveness of tested technologies was better manifested due to the great slope of parcels. Experimental plots had a length of 16 metres.

In total 4 technologies were selected to test and check the amount of organic matter washing away. Two technologies were selected as the control ones (Wischmeier & Smith 1978) and the two remaining technologies were soil conservation technologies

https://doi.org/10.17221/135/2018-SWR

with catch crops. In 2016 the experimental plots with catch crops were established always twice. For this reason, it was possible to carry out two rain simulations for each type of catch crop during one term. A more detailed description of tested technologies can be found in the following text:

(a) bare soil (control plot) – experimental plot is completely without plant cover,
(b) conventional farming (control plot) – the classical way of hop farming,
(c) conventional farming with sowing of *Phacelia tanacetifolia* – no-tillage sowing of *Phacelia tanacetifolia* in the amount of 10 kg/ha was carried out,
(d) chisel ploughing with the sowing of grass-legume mixture – no-tillage sowing of grass-legume mixture was carried out (*Pisum sativum* 20%, *Vicia sativa* 20%, *Avena sativa* 30%, *Triticum aestivum* 30%) in the amount of 120 kg/ha.

Rainfall simulator was used to measure soil erosion and consequent organic matter loss. It is a device which is used to a larger extent to study soil erosion processes, and the use of rainfall simulators is widely accepted (Chmelová & Šarapatka 2002; Iserloh *et al.* 2013; Martínez-Murillo *et al.* 2013; Lassu *et al.* 2015). The principle of measuring with rainfall simulator is based on rainfall simulation on a clearly defined and designated area. The size of the rainfall simulation area is 21 m^2, from which subsequently surface water along with eroded soil particles runs off. The rainfall simulator allows for monitoring not only the erosion effect, but also the rainfall and infiltration capacity of soil or the beginning and the end of surface runoff. Therefore, results and outcomes from a rainfall simulator offer a comprehensive set of information about selected technologies and their soil conservation effectiveness in the course of torrential rainfalls. When testing, it is necessary to ensure that soil and slope conditions of individual options are as similar as possible. For this reason the technologies were established and tested on the same plot.

Rainfall simulation on the designated area was done twice consecutively. The duration of the first rainfall simulation was 30 min, after which a technological 15-min break followed. After the allocated time elapsed, the second (repeated) rainfall simulation with duration of 15 min was performed. Two rounds of rainfall simulation were selected in order to simulate rainfalls on the soil with natural moisture and subsequently on the already saturated soil. Tests and checks of selected technologies were done in three developmental stages of the catch crop cover on growing dates defined in the guidelines Erosion Control in the Czech Republic – Handbook (Janeček *et al.* 2012). The description of individual growth dates is below:

(*I*) – date of measurement (second growth period) – period from plot preparation to sowing up to one month after sowing or planting
(*II*) – date of measurement (third growth period) – period to the end of second month from spring or summer sowing
(*III*) – date of measurement (fourth growth period) – from the end of the third period up to harvest

As for the rainfall simulator, the rainfall intensity is set to be 60 mm/h. Conditions described by Janeček *et al.* (2012) were taken into account when constructing the rainfall simulation regime. This intensity was chosen based on the recommendation of the Czech Hydrometeorological Institute and it reflects the average intensity of torrential rainfalls in the Czech Republic.

In order to determine the amount of organic matter washed away, it is necessary to know the total soil loss during simulation and the amount of organic matter in the eroded material. Firstly, the final soil loss for individually tested technologies has to be determined. Samples of surface runoff were always taken from the water-collecting flume at the place of outflow during the measurement using a rainfall simulator. Samples were taken every three minutes with the aim to find out the total amount of eroded undissolved particles. A calibrated container of 319 ml in volume was used with the sample taken to ensure the same volume of the taken sample every time. When the simulation finished, each sample was dried in a Memmert UFB 400 oven (Memmert, Germany) for 12 h at a temperature of 105°C in laboratory conditions. After drying, the weight of undissolved particles (mg) in each sample with the volume of 319 ml was determined. The number of samples varied in individual technologies depending on the beginning of surface runoff. The average amount of washed undissolved particles for the particular technology was determined from the samples treated in this way.

Due to the fact that the rainfall simulator detects the course and volume of surface runoff, it is possible to determine how much water ran off from the rainfall simulation area during the particular time. Total amount of eroded sediment from the checked area can be calculated by multiplying the average

https://doi.org/10.17221/135/2018-SWR

amount of undissolved particles in one sample by the volume of surface runoff.

Consequently, dried sediment from all samples for the particular technology was put together and the percentage amount of organic matter in the taken sediment was determined using the right method. In the laboratories of Research Institute of Soil and Water Conservation, the method ISO 14235 (1998), ÖNORM L 1081, was selected as the method determining the total amount of organic matter. If the percentage of organic carbon in the total amount of eroded undissolved particles is known, then the amount of washed organic matter during simulation can be determined as well.

RESULTS

The amount of washed away organic matter is related to bare soil, which is regarded as control technology along with conventional farming. Although the same method was observed during simulation, it is not possible to compare results for individual dates and years without converting them to percentage. This is so because the soil can have different moisture and temperature parameters when testing technologies. For this reason, the final values are expressed in percentage, when bare soil is considered the basis. In this way, the possibility to compare individual dates within one year and also across years is ensured. The average amount of undissolved particles converted to mg/l from all tested technologies is shown in Table 1.

For the first rainfall simulation the second growth period was chosen. Catch crops of the grass-legume mixture reached the height of 12–13 cm. The plants of *Phacelia tanacetifolia* were 5–6 cm high at the time of rainfall simulation. The problem seemed to be the effect on experimental plot caused by wheel tracks from agricultural machinery. Surface runoff occurred just in the wheel tracks.

The second date chosen for simulation corresponded to the third growth period. During the second measurement, the vegetation cover of catch crops was fully grown in both soil conservation technologies. The grass-legume mixture reached the height of 60 cm, whereas *Phacelia tanacetifolia* only 30 cm. The wheel tracks were the problem on both experimental plots again. However, plants started lodging due to rainfall simulation, among others also in the direction of the wheel tracks, thus better soil protection from direct fall of raindrops. The best protection of wheel tracks was manifested in cover crops of the grass-legume mixture which was more resistant to the traffic of agricultural machinery.

The third testing of chosen technologies was done in the fourth growth period. In the soil conservation technology with grass-legume mixture some crops were wilted (*Vicia sativa*, *Avena sativa*) but others (*Pisum sativum*, *Triticum aestivum*) still vegetated and reached the height of about 60 cm. A similar situation occurred also with the conventional farming of *Phacelia tanacetifolia*. In this period and individual plants started to wither. The height of *Phacelia tanacetifolia* was approx. 20 cm. The basic values from measuring with a rainfall simulator are shown in Table 2.

Rainfall simulation on soils with natural moisture – measured values during rain simulations on naturally moist soils are shown in Figure 1. A polynomial curve of 3rd degree (cubic polynomial) was chosen

Table 1. Rainfall simulation – average amount of undissolved soil particles in samples taken in tested technologies

Type of technology		Undissolved soil particles (mg/l per one sample)								
		I. term			II. term			III. term		
		2016 (a)	2016 (b)	2017	2016 (a)	2016 (b)	2017	2016 (a)	2016 (b)	2017
Bare soil	30 min	162 117	NA	168 860	51 049	NA	115 676	99 555	NA	107 738
	15 min	119 625	NA	81 663	73 096	NA	74 860	66 900	NA	54 419
Conventional farming	30 min	142 953	NA	137 410	55 450	NA	136 598	102 967	NA	131 134
	15 min	96 897	NA	63 764	50 097	NA	81 486	75 183	NA	64 939
C.f + *Phacelia tanacetifolia*	30 min	98 237	96 897	72 432	10 992	16 556	67 848	16 618	38 687	7 426
	15 min	88 461	95 531	39 034	8 444	12 986	36 359	9 653	37 909	4 107
C.p. + grass-legume mixture	30 min	142 412	156 962	104 212	5 913	14 363	28 985	33 689	54 356	20 246
	15 min	113 143	100 266	67 575	5 739	13 295	13 485	24 659	25 035	9 733

C.f. – conventional farming; C.p. – chisel ploughing; NA – not available – there was only one measurement for technologies of bare soil and conventional farming in 2016

https://doi.org/10.17221/135/2018-SWR

as a connecting line of the trend between the dates of rainfall simulation. As early as on the first date, a positive effect concerning the conservation of organic matter against washing away caused by water erosion was observed in soil conservation technologies. The washed amount of organic matter was similar in both treatments with catch crops and it ranged from 16% to 37% compared to bare soil. A significant influence of soil conservation technologies on reducing the organic matter loss was clearly apparent on the second date of simulation. With catch crops, the washing away of organic matter due to water erosion was reduced nearly by 75% (in 2017 nearly by 94% in the grass-legume mixture) in comparison with bare soil. During the third rain simulation, the tested soil conservation technologies retained strong conservation efficiency in relation to organic matter loss. This efficiency was around 75% in comparison with bare soil. Results of conventional farming point out to the insufficient protection of hop garden inter-rows against organic matter washing away. The extent of organic matter washing away was usually significantly higher than the values obtained when using catch crops.

Rainfall simulation on already saturated soils – the washed away amount of organic matter during rain simulations on already saturated soils is depicted in Figure 2. The cubic polynomial was used again for the curve of development concerning technology conservation efficiency between the dates of rainfall simulations. The highest organic matter loss on the first date of rainfall simulation occurred on plots with control treatments (2016 – conventional farming, 2017 – bare soil). Differences in the total

Table 2. Measured values during the rainfall simulation

Term	Type of verified technology		No. of samples			Surface runoff (l)			Organic matter in sediment (%)		
			2016 (a)	2016 (b)	2017	2016 (a)	2016 (b)	2017	2016 (a)	2016 (b)	2017
I. term	Bare soil	30 min	10	NA	9	360	NA	490	1.16	NA	1.24
		15 min	6	NA	6	225	NA	206	1.09	NA	1.25
	Conventional farming	30 min	9	NA	10	290	NA	323	1.18	NA	1.11
		15 min	6	NA	6	263	NA	228	1.17	NA	1.12
	C.f. + *Phacelia tanacetifolia*	30 min	7	5	9	209	102	242	1.17	1.26	1.32
		15 min	6	6	6	212	174	240	1.31	1.30	1.51
	C.p. + grass-legume mixture	30 min	8	8	9	130	137	145	1.33	0.90	1.13
		15 min	6	6	6	212	219	167	1	0.88	1.19
II. term	Bare soil	30 min	10	NA	10	286	NA	420	1.20	NA	1.11
		15 min	6	NA	5	225	NA	249	1.07	NA	1
	Conventional farming	30 min	10	NA	9	280	NA	304	0.96	NA	0.89
		15 min	6	NA	5	205	NA	202	0.97	NA	0.90
	C.f. + *Phacelia tanacetifolia*	30 min	10	10	9	261	254	142	1.67	1.42	1.28
		15 min	6	6	6	149	171	107	1.86	1.22	1.28
	C.p. + grass-legume mixture	30 min	10	10	9	261	251	74	2.11	1.35	1.48
		15 min	6	6	5	152	155	58	1.82	1.21	1.66
III. term	Bare soil	30 min	10	NA	11	385	NA	503	1.19	NA	1.42
		15 min	6	NA	6	265	NA	272	0.87	NA	1.12
	Conventional farming	30 min	10	NA	11	352	NA	294	1.01	NA	1.21
		15 min	6	NA	6	271	NA	157	0.96	NA	1.35
	C.f. + *Phacelia tanacetifolia*	30 min	11	11	11	419	423	353	1.21	1.15	1.92
		15 min	6	6	6	232	152	232	1.53	1.12	1.94
	C.p. + grass-legume mixture	30 min	11	10	11	422	323	279	1.04	1.09	1.58
		15 min	6	6	6	238	240	168	1.08	1.05	1.66

C.f. – conventional farming; C.p. – chisel ploughing; NA – not available – there was only one measurement for technologies of bare soil and conventional farming in 2016

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amount of washed away organic matter decreased in all tested technologies compared to rainfall simulation on naturally moist soils. The main reason is soil saturation from the previous rainfall simulation and low growth of catch crops. Even still, the soil conservation technologies showed lower values than bare soil and conventional farming. Both treatments with catch crops were already fully engaged when rainfall simulation on saturated soils was performed on the second date. This was demonstrated also in high soil conservation resistance to organic matter loss. Organic matter washing away in the case of using catch crops was lower by approx. 85% compared to bare soil. On the third date, soil conservation technologies showed high conservation efficiency. Both treatments with catch crops reached similar results during measuring. Washing away in inter-rows with catch crops was lower on average by 29% compared to bare soil. Technologies of conventional farming had again weak soil conservation effects on all dates of measurement. On the third date in 2016, organic matter washing away was even higher by 26% compared to bare soil.

Evaluation of the two-year research – based on the two-year research, bare soil is considered the worst treatment; it was chosen as the control plot and results of other technologies were related to it. Results of conventional farming are not significantly different compared to bare soil. This fact points out to the insufficient soil conservation efficiency of traditional farming. During the second rainfall simulation on already saturated soil, conventional

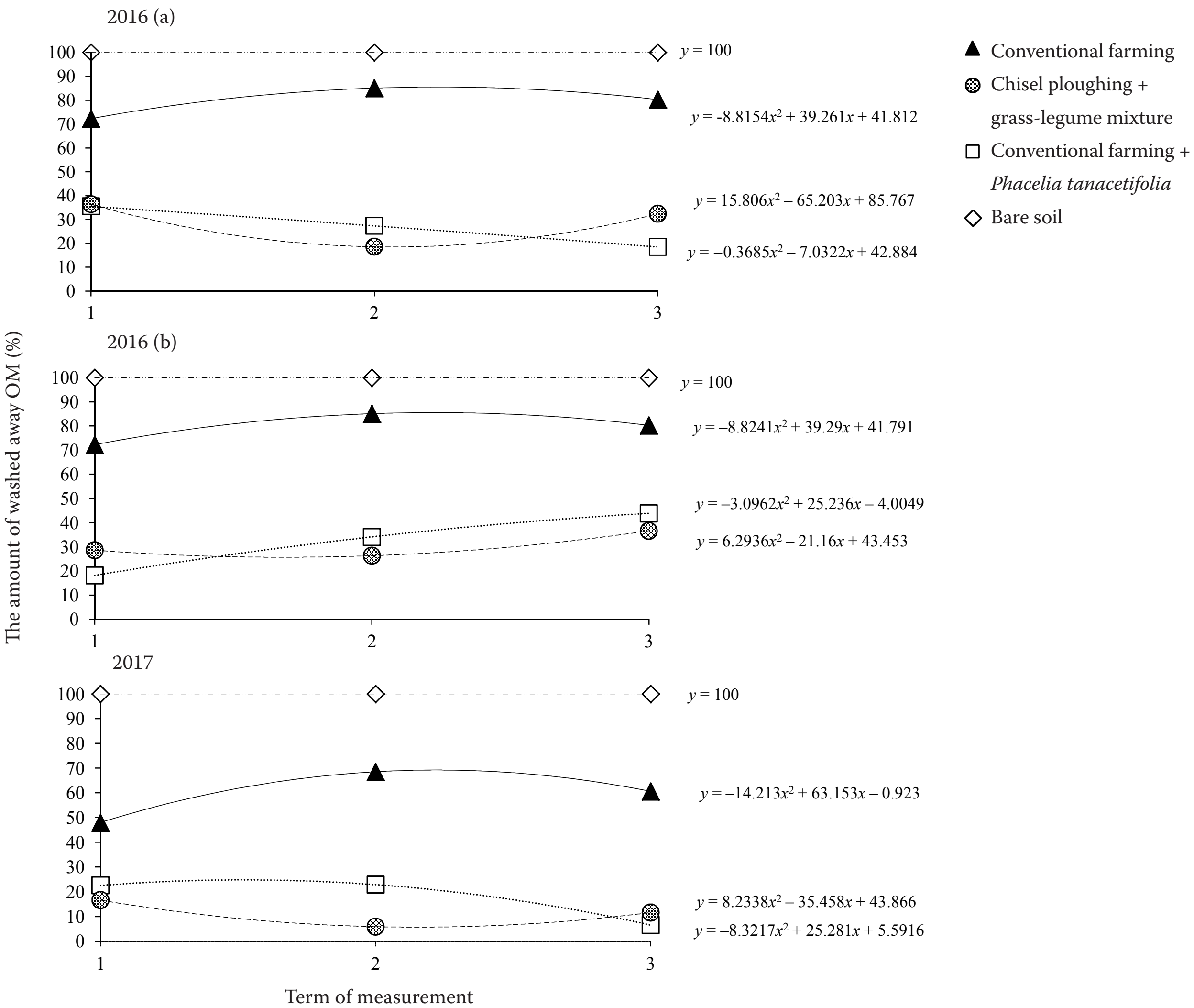

Figure 1. The amount of organic matter (OM) washed away during rain simulations on naturally moist soil (first simulation – 30 min)

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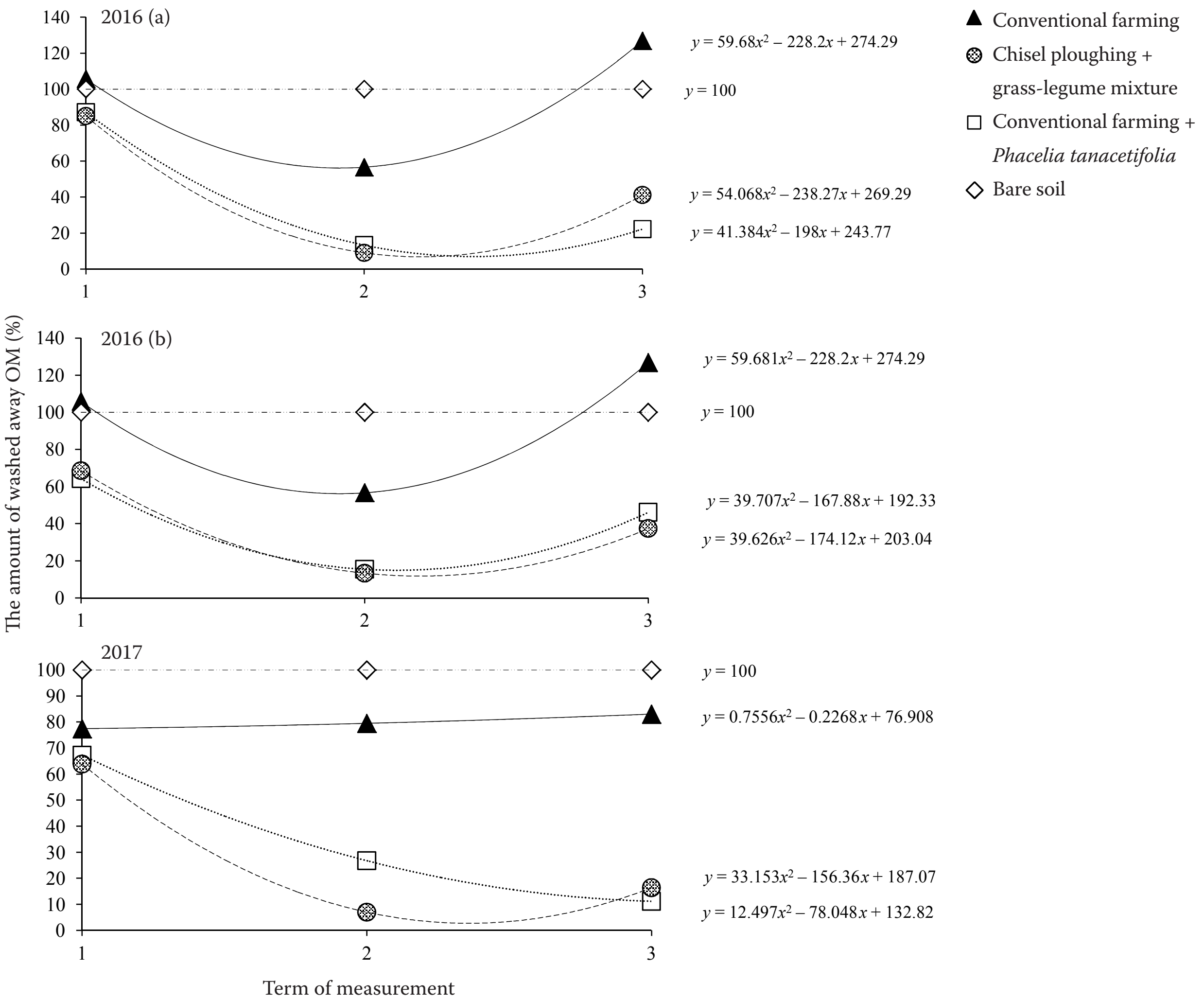

Figure 2. The amount of organic matter (OM) washed away during rain simulations on already saturated soil (second simulation – 15 min)

farming was worse in two cases compared to bare soil. Compared to the treatments with catch crops, this is a technology whose soil conservation efficiency is very low. The average amount of washed away organic matter from the two-year research is depicted in Figure 3 including an error line segment describing the deviation between the measurements.

It follows from acquired data that by using catch crops it is possible to reduce the organic matter loss from soil in the course of the entire season by more than half compared to conventional farming; both in the case of rain on naturally moist soils (66.2%), and also in the case of repeated rain on already saturated soils (59%). In all measured cases the amount of washed away organic matter was lower compared to control plots (bare soil, conventional farming). Catch crops fulfil their soil conservation function even shortly after sowing. Their efficiency increases in the course of the season up to full growth. The technologies with catch crops still maintain a high degree of soil conservation efficiency even after the end of vegetation season. One of the most important indicators of this research is depicted in Figure 4. There exists conservation efficiency of catch crops on individual dates of measurements in relation to conventional farming. The conservation effect concerning organic matter washing away due to water erosion was generally very high in the treatments with catch crops. An exception is the first date with rainfall simulation on already saturated soil. On this date the plants of catch crops do not yet reach necessary height and the soil conservation effect is not so significant as in the following measurements due to soil saturation from the previous rainfall simulation.

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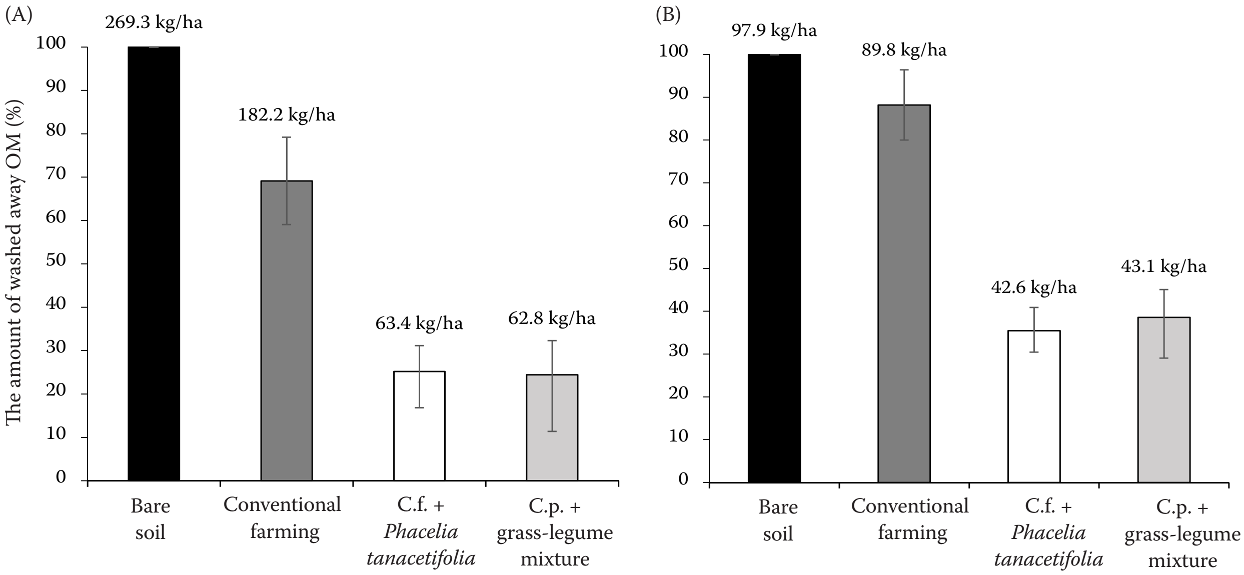

Figure 3. Average amount of washed away organic matter (OM) during simulations in 2016 (a, b) and 2017: naturally moist soil – 30 min simulation (A) and saturated soil – 15 min simulation (B)
C.f. – conventional farming; C.p. – chisel ploughing

DISCUSSION

A characteristic feature of soil conservation technologies during soil cultivation is leaving the residues of preceding crops or biomass of catch crops on the soil surface or only a shallow ploughing of these plant residues into the soil (Alberts & Niebling 1994). The same was claimed by Blanco and Lal (2010), who dealt with principles and management of soil conservation. The most important outcome of this research is the finding of a difference in the amount of washed away organic matter due to water erosion between conventional farming and technologies with catch crops. A direct correlation between erosion and soil management has been found by many authors. The lower the extent of erosion, the lower is the organic matter loss from soil. Some authors have found that soil conservation technologies reduce the erosion risk by up to 63% compared to conventional farming (Zhang *et al.* 2009). Novara *et al.* (2011) reported a reduction of erosion with catch crops from 40% to 76% in comparison with conventional technology. These results are in line with Marques *et al.* (2010). In a two-year study at the plot scale Ruiz-Colmenero *et al.* (2011) observed that inter-rows with a cover crop lost between 50% and 75% less soil than inter-rows without cover crops. Biddoccu *et al.* (2017) stated that the annual sediment

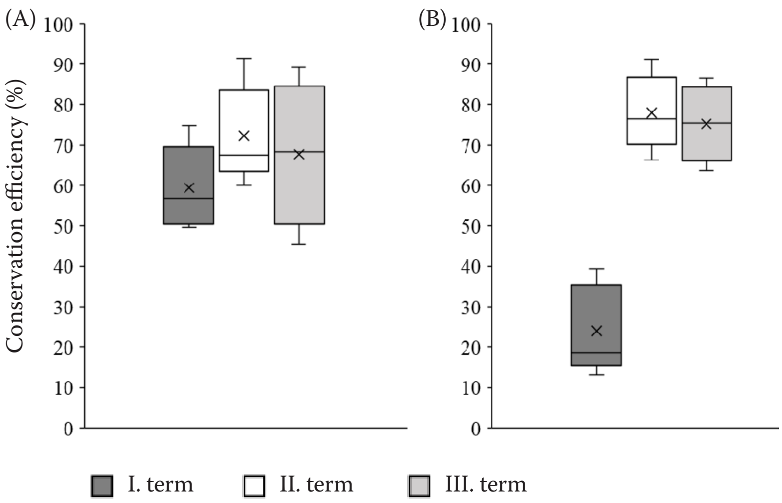

Figure 4. Conservation efficiency of catch crops compared to conventional farming: naturally moist soil – 30 min simulation (A) and saturated soil – 15 min simulation (B)

https://doi.org/10.17221/135/2018-SWR

yield in cover crops was lower by 72% to 89% than in conventional farming. Also, Morvan *et al.* (2014) measured low erosion rates for vegetation covered plots and pointed out the importance of grass cover density in the wheel tracks of agricultural machinery to prevent water runoff and erosion.

Conclusions of this study are similar. When there are catch crops in inter-rows, erosion and washed away organic matter are much lower compared to conventional farming which is without vegetation cover. The values of other authors do not differ very much from our results when the difference in organic matter washing away between soil conservation treatments and conventional farming was on average lower by 60% on naturally moist soils, and by 54.5% on soils already saturated. Some authors like Wendt and Burwell (1985) recorded a reduction of erosion higher than 90%. In this way García-Orenes *et al*. (2005) stated that catch crops, by their very presence, are able to protect the soil surface against the effect of rain drops. Moreover, catch crops reduce the amount of surface runoff and they support the formation and stability of soil aggregates. As it was mentioned by Fullen *et al*. (2006), the organic matter content in soil under 2% already significantly increases the risk of erosion. In the longer-term use of catch crops, a favourable influence on yields of main crops and on soil structure can be expected (Javůrek & Vach 2009).

CONCLUSION

The issue of organic matter loss from erosion threatened plots of hop gardens is a significant one. Because the amount of washed away organic matter was lower in soil conservation technologies in all realized measurements compared to conventional farming, it can be concluded that catch crops significantly reduce the organic matter loss in hop gardens vulnerable to erosion. On the contrary, measured values in conventional farming point out the need of using a different farming method for hop gardens if they are located on hillside plots. During the season, the amount of washed away organic matter in plots with catch crops was reduced by more than half compared to conventional farming. The soil conservation effect of technologies gradually increased in the course of the catch crop growth. The most vulnerable period is the time until the catch crop cover is at least partially closed. Nevertheless, catch crops show a significant soil conservation effect even in the first stage. Maximum soil conservation effects were found on the second date of measurement, which was done by the end of June. Thus, during the periods of the most frequent occurrence of torrential rains, catch crops prevented organic matter loss from the plot threatened by erosion.

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Determination of C-factor for conventional cultivation and soil conservation technique used in hop gardens.

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Research Article

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Determination of C-factor for conventional cultivation and soil conservation technique used in hop gardens

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Abstract: The research presented in the article was focused on determining the C-factor for hops for conventional cultivation (CT) and soil conservation technique, which is based on the presence of cover crops (CC) in the inter-rows. The values of the soil loss ratio, which are the basis for the calculation of the C-factor, are also presented. The research activities were carried out between 2016 and 2023 and a field rainfall simulator was used for the measurements. Rainfall simulations were conducted at three developmental stages of CC. The results show a high C-factor value for CT (0.73), which indicates insufficient erosion control efficiency. In contrast, a C-factor of 0.16 was determined for the cover crop technique. This means that cover crops in the inter-rows of hop gardens can effectively reduce the risk of water erosion. The values reported in the article can be used as input parameters in various erosion models and equations to refine the subsequent calculation.

Keywords: water erosion, rainfall simulator, soil degradation, permanent crops, cover crops

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1 Introduction

Water erosion is one of the most common and serious degradation processes occurring on agricultural land worldwide [1,2]. Nowadays, there are efforts to reduce the extent of water erosion through soil conservation techniques (SCTs) [3,4]. SCTs are very often based on a high surface cover of plants or plant residues [5]. When calculating the erosion control efficiency of a particular technique, the conservation effect of vegetation (so-called C-factor) is one of the important parameters [6–11]. This is an indicator that is part of the most widely used erosion models, which are mainly the Universal Soil Loss Equation [9] and the Revised Universal Soil Loss Equation derived from it [11].

C-factor is defined as a dimensionless number that varies between the values of 0 and 1, which is influenced by several parameters: prior land use, canopy cover, surface cover, surface roughness, and soil moisture [12]. A bare soil (BS) without vegetation with the parameters specified in Yoder et al. [12] represents number 1 and means high soil loss (SL). It is also taken as a control technique. Other farming methods are related to BS according to predetermined conditions [7]. The closer the number is to 0, the lower the extent of water erosion. The determination of the resulting C-factor always takes place in different cropstage periods. The numbers soil loss ratio (SLR) obtained from the cropstage periods is further corrected by the percentage distribution of the R-factor (rain erosivity) during the year [13].

In this article, the erosion control efficiency in hop gardens is evaluated in terms of the conservation effect of vegetation. Hops are typically grown in rows [14]. The width of the inter-rows is most often between 2.7 and 4.2 m [15]. This space is kept free of vegetation cover by shallow cultivation, which is carried out several times a year [14,16]. There are also specific agrotechnical operations that are typical only of hop gardens (hop pruning in spring or ploughing the soil to the plants) [17]. All these agrotechnical operations cause that in conventional cultivation

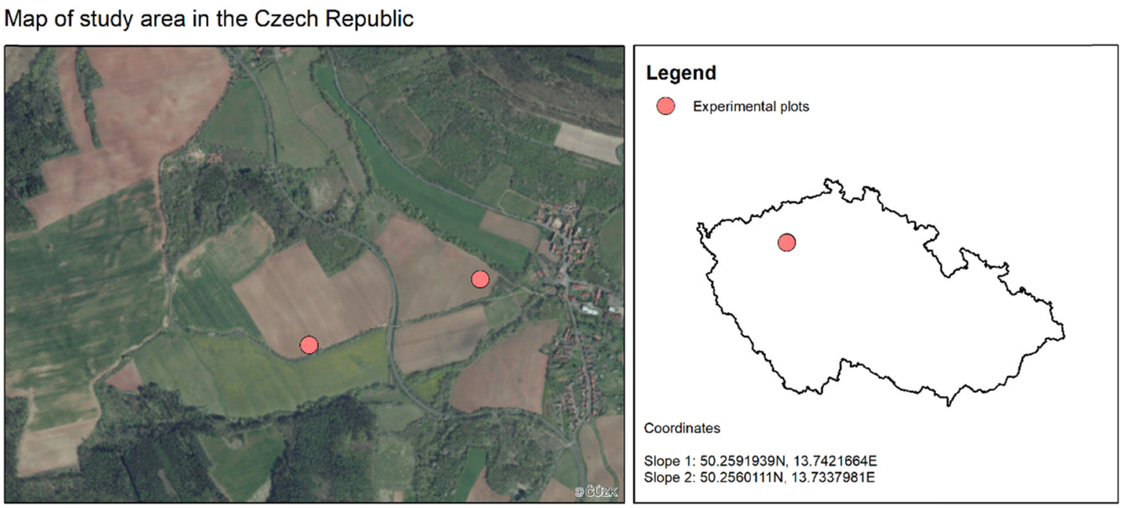

Figure 1: Location of experimental plots within the Czech Republic. Source: ČÚZK, 2023.

(CT), the soil surface is not sufficiently protected against water erosion [18]. Hop is therefore one of the most erosion-prone agriculture crops ever. If the hop garden is sloping, the soil is carried away with every torrential rain. Unfortunately, the number of SCTs that can be used in hop gardens or other permanent crops is limited due to the way they are grown (in rows) and the presence of a hop construction.

Cover crops (CC) sown in between the rows are proving to be a solution. These have a number of positive aspects in addition to their soil conservation effect [19]. The aim of this article is to present the following information: (1) determine the C-factor for CT; (2) determine the C-factor for the SCT using CC; and (3) monitor how much the C-factor and SLR values change over the season in different cropstage periods.

2 Methods

The research was conducted between 2016 and 2023 near the village of Solopysky (50.2591939N, 13.7421664E; 50.2560111N, 13.7337981E), which is located in Central Bohemia in the Czech Republic (Figure 1). The average annual temperature in the region is 7–8.5 °C, and the annual precipitation is 450–550 mm. Soils in the experimental plots were luvic Cambisols [20]. The topsoil layer is up to 50 cm. The basic soil properties were as follows: the soil texture: <0.002 mm 23.8%, <0.01 mm 36.5%, <0.05 mm 66.7%, <0.1 mm 84.4%; total oxidizable carbon (C_{ox}) 1.53%; and humus 2.64%. The research took place on two uniform slopes that had a slope of 17 and 9%. In each year, experimental plots were established in the spring (late March to early April). During establishment, CC were sown (standard amount for each species) at the same time, always in three replications due to three rainfall simulation (RS) terms. Thus, RS were always performed on an unsimulated surface. Hop plants and CC were only affected by natural rainfall. The length of each experimental plot was 16 m (slope 17%) and 32 m (slope 9%). During the year, all necessary agrotechnical operations were carried out on the experimental plots. The different management methods can be seen in Figure 2.

In total, three techniques were selected to test soil conservation efficiency. The first was BS, which was a control technique [9]. The other two remaining techniques were CT and SCT with different kinds of CC. During the research, six plant species were tested. The following text contains a more detailed description of the tested methods:

(a) BS (control plot) – the experimental plot is flat and completely without plant cover. Before each simulation on naturally moisture soil was performed loosening the top layer of soil up to 5 cm and then rolling it with a roller weighing 50 kg. This procedure was chosen based on methodologies Wischmeier and Smith [9] and Janeček et al. [13].

(b) CT – the classical way of hop farming, inter-rows without plant cover, loosening the soil several times a year. The hops are pruned in spring and the soil is ploughed to the plants in the second half of May. The harvest is usually at the end of August. Compared to BS, the soil surface of CT has a coarser structure and contains compacted soil at the places of the traffic wheels.

(c) SCT with CC – no-tillage sowing of selected plants (*Phacelia tanacetifolia* Benth.; *Sinapsis alba* L.; *Secale cereale* L., *Trifolium incarnatum* L., grass–legume mixture 1: *Avena sativa* L., *Vicia sativa* L., *Pisum sativum* L.,

Figure 2: CT (left), *Phacelia tanacetifolia* Benth. (middle), and grass–legume mixture 2 (right) at the end of period 2. Source: Photo taken by the authors.

Figure 3: Rainfall simulator in hop garden (end of cropstage period 1). Source: Photo taken by the authors.

Triticum aestivum L.; grass–legume mixture 2: *Avena sativa* L., *Vicia sativa* L.) in inter-rows of hop-gardens at the beginning of spring. There is no loosening the soil during the year. Mulching of the plants is also possible if necessary. At the end of the season (after harvest), the CC are shallowly plowed back into the soil.

A field rainfall simulator was used as the main research method (Figure 3). From the measuring, it is possible to calculate the SL, on the basis of which it is possible to further calculate the resulting value of the C-factor. The rainfall simulator is a suitable device that is used to study soil erosion processes on sloping land [21,22]. This device allows monitoring of the erosion effect, infiltration capacity of soil, or the beginning and the end of surface runoff. The amount of surface runoff was determined in a tipping bucket. The basic principle of measuring with a rainfall simulator is the spraying of water on a clearly defined area. The size of the simulating area was $21\,m^2$ (9.0×2.33 m), and the intensity of the rainfall was always set at about 1 mm/min. The rainfall simulator used for research had four nozzles (fulljet type) at the height of 2.0 m. All nozzles covered an area up to an angle of 104° at a pressure of 34.5 kPa. The average raindrop diameter was 1.5 mm to 2.0 mm, and the average kinetic energy of the raindrops accounted for $8.78\,J\,m^{-2}\,mm^{-1}$.

When measuring, it was necessary to ensure that the soil, slope, and climatic conditions of individual techniques were as similar as possible. For this reason, all experimental plots were established side by side, tested on the same slope and on the same day. Two repeated RS were performed. The duration of the first RS was 30 min on naturally moisture soil. Then, there was a 15-min technological break. After this time, a second (repeated) RS was performed on soil with higher moisture for a duration of 15 min. Two RS at different soil moistures were performed due to comprehensive verification of the soil conservation effectiveness of the measured technique.

Monitoring of erosion control effectiveness must be spread over the entire year, as it varies with crop growth. The method of determining the C-factor is therefore divided into five cropstage periods, which are defined in the guidelines "Predicting rainfall-erosion losses from cropland east of the Rocky Mountains: Guide for selection of practices for soil and water conservation" [7]. The description of individual cropstage periods is defined as follows:

- Period F (rough fallow): turn plowing to seeding.
- Period I (seedling): seedbed preparation to 1 month after planting.
- Period II (establishment): from 1 to 2 months after spring or summer seeding.
- Period III (growing and maturing crop): end of period 2 to crop harvest.
- Period IV (residue or stubble): crop harvest to plowing or new seeding.

RS were performed for periods I, II, and III. Periods F and IV (periods outside hop and CC vegetation) were taken from Wischmeier and Smith [7]. To determine the amount of SL, samples of surface runoff with soil particles were taken from the water-collecting flume at the place of outflow in the lower part of the experimental area. Samples were taken every 3 min into the calibrated container of 319 ml in volume after surface runoff started. Subsequently, each sample was dried in a Memmert UFB 400 oven (Memmert, Germany) for 12 h at a temperature of 105°C in a soil laboratory.

After drying, the weight of soil particles (mg) in each sample with a volume of 319 ml was determined. The resulting SL for each interval was calculated by multiplying the soil particles' values by the amount of surface runoff. From these values, the SL was calculated for each technique. For the SCT, we did a statistical calculation to see if there was a difference between individual species. No statistical significance was found, so the article continues to calculate with CC regardless of species (Figure 4).

If the SL and other important parameters are known, it is possible to calculate the C-factor. SL values as the sum of two RS (first plus second simulation) were used to calculate the SLR (Table 5). The resulting SLR value was further corrected by the canopy cover (hop plants) subfactor presented in Reinard et al. [11]:

$$CC^1 = 1 – Fc \times \exp(-0.1 \times H),$$

where CC^1 is the canopy cover, Fc is the fraction of the land surface covered by a canopy, and H is the distance that raindrops fall after striking the canopy. The main reason for this correction is that hop plants were not included in the inter-row space during the simulations. The correction took into account the changing Fc and H parameters as the hops grew.

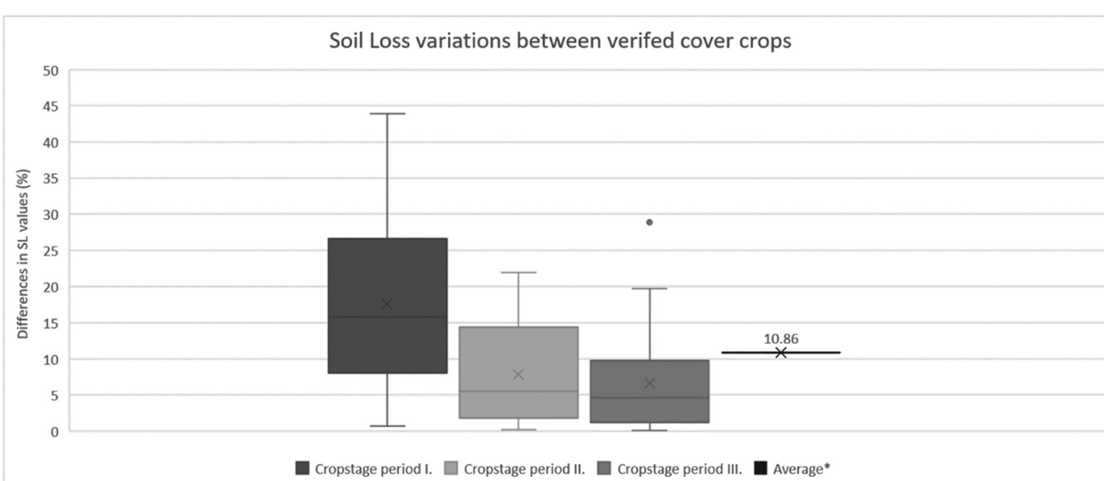

Figure 4: Measured variations in SL between individual CC at cropstage periods (I, II, and III) from all measurements from 2016 to 2023; *SL – Soil Loss; there was no statistically significant difference (P-value < 0.05, Mann–Whitney U test) in erosion control efficiency between plant species (*Phacelia tanacetifolia* Benth.; *Sinapsis alba* L.; *Secale cereale* L., *Trifolium incarnatum* L., grass–legume mixture 1; grass–legume mixture 2); Average – average variation from all measurements.

Table 1: Number of rainfall simulator measurements for the verified techniques

Type of technique	Year								Total
	2016	2017	2018	2019	2020	2021	2022	2023	
BS	6	6	6						18
CT	6	6	6	4	6	6	6	6	46
CC	36	36	36	8	12	12	12	12	164
Phacelia tanacetifolia Benth.	12	12	12						36
Sinapsis alba L.				4	6	6	6	6	28
Grass–legume mixture 1	12	12	12						36
Grass–legume mixture 2				4	6	6	6	6	28
Secale cereale L.	6	6	6						18
Trifolium incarnatum L.	6	6	6						18

The SLR for all cropstage periods (F, I, II, III, and IV) was multiplied by the percentage distribution of the R-factor (rain erosivity) in the evaluated period to obtain the partial C-factor. The percentage distribution of R-factor for the conditions of the Czech Republic determined according to Janeček et al. [13] is shown in Table 2 and is based on the long-term monitoring of the Czech Hydrometeorological Institute.

In this way, the C-factor was determined for both CT and SCT in inter-rows of hop gardens. For CT, the resulting C-factor was determined after the first 3 years of research (2016–2018), and for SCT from eight measured years (2016–2023). Since 2019, BS was no longer verified, but only CT and SCT are verified (Table 1). Thus, the measured SL results for the SCT were always percentage recalculated based on the SL for CT and BS. The aim was to relate the measured numbers to the value of 1 (BS) and not to the value for CT. This process was carried out for all RS carried out after 2019.

SL data from CT and SCT were analyzed to test for statistically significant differences between cultivation methods. First, the Shapiro–Wilk test for normality of the data was performed. Because some of the data sets did not have a normal distribution, the Mann–Whitney *U* test at the significance level $P < 0.05$ was chosen. The same process was performed to verify the difference between CC species.

Table 2: Percentage distribution of the R-factor by month in the Czech Republic according to Janeček et al. [13]

Month	IV	V	VI	VII	VIII	IX	X
R-factor (%)	1	11	22	30	26	8	2

Table 3: Soil loss in individual cropstage periods

Cropstage period	First RS				Second RS				First plus second RS			
	CT		SCT		CT		SCT		CT		SCT	
	SL*	SD*	SL*	SD*	SL*	SD*	SL*	SD*	SL*	SD*	SL*	SD*
F	—	—	—	—	—	—	—	—	—	—	—	—
I	0.62a	0.08	0.30b	0.13	0.81a	0.08	0.63a	0.20	0.71a	0.02	0.47b	0.14
II	0.83a	0.12	0.19b	0.18	0.86a	0.09	0.21b	0.24	0.84a	0.10	0.20b	0.21
III	0.87a	0.13	0.21b	0.22	0.91a	0.19	0.17b	0.17	0.89a	0.16	0.19b	0.20
IV	—	—	—	—	—	—	—	—	—	—	—	—
Average	0.77	0.11	0.23	0.18	0.86	0.12	0.34	0.20	0.81	0.09	0.29	0.18

*SL – soil loss, SD – standard deviation; Statistical evaluation was performed for the rainfall simulator data. First, the Shapiro–Wilk test for normality. Then, the Mann–Whitney *U* test was performed to determine statistical significance (both statistical tests at the $P < 0.05$ significance level). CT and SCTs were always compared at the individual cropstage period. Cropstage periods F and IV were not measured with the rainfall simulator. The values of the sum of two RS were used to calculate the SLR. The values in the table are related to BS, which represents the number 1.

Table 4: Basic statistical tests for rainfall simulator data

Cropstage period	I		II		III	
Type of cultivation technique	CT	SCT	CT	SCT	CT	SCT
First RS						
Shapiro–Wilk test	0.23	0.33	0.04	>0.01	0.06	>0.01
Mann–Whitney *U* test	0.011		>0.001		0.006	
Second RS						
Shapiro–Wilk test	0.26	0.09	0.26	>0.01	0.06	>0.01
Mann–Whitney U test	0.180		>0.001		0.003	
First plus second RS						
Shapiro–Wilk test	0.54	0.11	0.76	>0.01	0.07	>0.01
Mann–Whitney *U* test	0.029		>0.001		0.005	

Mann–Whitney *U* test – H_1: $Group_1 > Group_2$ (*P*-value < 0.05). Shapiro-Wilk test (*P*-value < 0.05).

3 Results and discussion

3.1 SL and partial C-factor in individual cropstage periods

Period F (rough fallow): in this period (approximately the end of March to the first half of April), the surface in the inter-rows is completely without plant cover. The soil is being prepared for the new hop growing season: the surface is being smoothed with ridge harrows, the hops are being proned or wiring is done. As soon as suitable climatic conditions appear, it is necessary to sow the CC. It is important to sow them when there is still enough moisture in the soil after the winter. This will then affect the quality of the CC for the rest of the season. As there are no crop residues in the inter-row at this time, we calculated with the value taken from Wischmeier and Smith [7] for the rough fallow of 0.7 for both verified techniques. A value of 0.7 is given in the publication for conventional tillage in maize cultivation (residue of prior crop removed, cropstage period F). The surface character of the soil in the inter-row of hop gardens can therefore be considered similar. According to Table 2, there is no torrential rainfall yet in this period. Thus, period F does not affect the resulting C-factor. It is valid for the conditions of the Czech Republic, as in other climatic conditions there can be the occurrence of torrential rainfall even in this period.

Period I (seedling): According to Janeček et al. [13] and Wischmeier and Smith [7], this cropstage period starts on the day of sowing and ends on the day that closes 1 month after sowing. CC are in early growth (for hop gardens in the Czech Republic, it is mainly April). This corresponds to their soil conservation efficiency (Table 3), which increases with progressive growth. In this cropstage period, there were the largest differences (not statistically significant) between CC species (Figure 4). This is mainly due to differences in growth dynamics.

Already 1 month after sowing, CC have a significant soil conservation effect if the RS is carried out on soil with natural moisture. For the second RS, the soil conservation effect is not statistically significant enough. This is mainly because the soil had a higher initial moisture content, and CC were still in their early growth. However, the value of the sum of the two RS is used to calculate the SLR, and in this case, the statistical difference was also confirmed (Tables 3 and 4). In this cropstage period, it is necessary to start correcting the resulting SL in the SLR calculation due to the gradual growth of the hop plants. Hop plants cover approximately 10% of the surface and reach a height of 1 m. These values may vary in part depending on the climatic conditions in a given year. In the Czech Republic (central Europe), torrential rainfall starts to occur in April, but the probability of occurrence is low. As a result, the C-factor for both CT and SCT is also low (Table 5).

Period II (establishment): during the second cropstage period, the CC gradually reach full growth, and their soil conservation effect reaches its maximum effect [23]. Significant SL reduction then occurs in the first, second, and also in the sum of RS. The average SL is 0.2 at the end of this period, so it can be concluded that SCT effectively protect the soil from water erosion. In contrast, the SL for the CT remains high and is even slightly higher than in the previous period (mainly due to the lower amount of moisture in the soil). Hop plants continue to grow, reaching a height of approximately 3 m and covering 20% of the surface. In this period, other benefits of CC start to become apparent, for example, flowering species (*Phacelia tanacetifolia* Benth) attract large numbers of pollinators. The probability of erosive rainfall increases to 11% in May. This is reflected in an increase in the C-factor for the CT for this period. For the SCT, the C-factor is still very low due

Table 5: C-factor by cropstage periods for CT and SCT with CC

Cropstage period	CT					SCT				
	SL*	Canopy cover (hop plants) correction	SLR	Percentage distribution of the R-factor	Partial C-factor	SL*	Canopy cover (hop plants) correction	SLR	Percentage distribution of the R-factor	Partial C-factor
F^x (1. 11.–20. 3.)	—	—	0.70	—	0.00	—	—	0.70	—	0.00
I (21.3.–30. 4.)	0.71	0.91	0.65	0.01	0.01	0.47	0.91	0.43	0.01	0.00
II (1. 5.–31. 5.)	0.84	0.85	0.71	0.11	0.08	0.20	0.85	0.17	0.11	0.02
III (1. 6.–31. 8.)	0.89	0.84	0.75	0.78	0.58	0.19	0.84	0.16	0.78	0.12
IV^x (1. 9.–31. 10.)	—	—	0.62	0.10	0.06	—	—	0.24	0.10	0.02
C-factor	**CT**				**0.73**	**Conservation technique with CC**				**0.16**

*SL (Soil Loss) sum of values from both RS; SLR (Soil Loss Ratio); The values in the table are related to BS, which represents the number 1; F^x and IV^x values were from the Wischmeier and Smith [7] – modified for hop-growing conditions. In cropstage periods F and IV, there were no hop plants on the plot; therefore no canopy cover correction.

to the high surface cover. This is especially important for the following III cropstage period.

Period III (growing and maturing crop): this cropstage period is considerably longer in terms of time than the previous periods and has the most significant impact on the resulting C-factor. This is most often the end of May or the beginning of June until the harvest, which is usually toward the end of August (for the Czech Republic). The length of the growth of the CC is influenced by the choice of the species and varies. However, even wilting plants remain in the inter-row and fulfil their soil conservation function, which is still very high compared to CT. From this point of view, the grass–legume mixtures looked better. The SL is still low at around 0.19. For CT, the SL continues to increase to a very high value of 0.89 in the sum of RS. Hop plants at this period usually reach the top of the hop construction (they can be bent over), which is often 6 m high. They also increase their surface coverage, which is around 30%. These values are taken into account in the correction of the SLR calculation. Some studies [24–26] have focused on the effect of large drops dripping from plant leaves on SL due to larger kinetic energy and falling height. This fact may be relevant in the case of hop, as the mature plant has large leaves and reaches great heights. These parameters are included in this study as part of the correction made by the formula [11], which is presented in Section 2.

Period IV (residue or stubble): after the harvest comes the final cropstage period, which is also long (September, October). The hop plants are no longer in the hop gardens, and the soil surface is cleaned after harvest. The CC should be ploughed shallowly into the soil after harvest to return the organic matter and nutrients. Thus, a kind of stubble is present in the inter-row. Wischmeier and Smith [7] give the SLR 0.24 for a similar type of soil cultivation (minimum tillage – residue crop left, cropstage period IV). We therefore also use this value when calculating the C-factor. In CT, the inter-row remains bare without cover. For this reason, the SLR value 0.62 was chosen. This value means (as well as in period F) conventional tillage in maize cultivation (residue of prior crop removed, cropstage period IV). The frequency of torrential rainfall decreases to 8% in September and 2% in October in the Czech Republic.

3.1.1 C-factor value

The C-factor for CT was determined in the first 3 years. When compared to BS, CT is not significantly different in terms of cover in the inter-rows. As the inter-rows are loosened several times during the season, there were also no plant residues in this area. Some weeds may be present, especially in the time before the loosening. Despite the similar character of the inter-rows, the SLR measured for the CT was lower than for the BS (Table 3). This is mainly due to the different soil structure. In BS, the simulated area is levelled, loosened, and then rolled over with a roller weighing 50 kg. With CT, the soil in the inter-rows has a coarser structure and there may be larger soil aggregates (Figure 2). This affects the resulting amount of surface runoff and SL. There is also a difference in the presence of hop plants compared to BS. The resulting value of the C-factor for CT was determined to be 0.73. This value was determined based on a total of 18 measurements in 2016–2018 (Table 1). The value is less than 1, but still very high. This fact confirms that water erosion in hop gardens is a serious problem and that CT is insufficient in terms of soil conservation. The value that we have determined is in general agreement with other authors who have tried to determine the C-factor in hop gardens. Janeček et al. [13] state, in their methodology, the C-factor value for hop gardens of 0.8. Similarly, Auerswald et al. [27] set the C-factor in hop gardens at 0.78, and Malíšek [28] set the value at 0.73. Our value is similar to these numbers and provides a validation framework to confirm the accuracy of the measurements.

After the C-factor for the CT was determined, we continued to verify the SCT in order to determine the C-factor for this technique as well. The resulting C-factor for the SCT in the hop gardens was determined by 0.16. There is currently a lack of information on similar research in the scientific literature, and therefore, the results can be considered unique. Some studies about water erosion in hop gardens can be found, especially in Germany, but they are very rare. For example, Schwertmann and Schmidt [29] or Schauder and Auerswald [30] who used copper as a tracer in deposition.

In this study, the C-factor for the SCT was determined based on 164 measurements with the rainfall simulator for six types of CC in inter-rows between 2016 and 2023. The measured SL values from the individual RS, given in units of t/ha, are shown in Figure 5.

Some comparison can be made via SL with other permanent crops that are similar in their character of inter-rows cultivation (vineyards, orchards). The total SL in CT as a sum from RF is 81% (Table 3). Capello et al. [31] measured an 83% lower SL in vineyards with grass-covered plots in vineyards. Similarly, Biddocu et al. [32] report lower SL ranging from 72 to 89%. Napoli et al. [33] reported a reduction of 68.5% in SL, and also Bagagiolo et al. [34] did not differ much in their results (lower SL at the two experimental sites of 78 and 80%, respectively). In almond orchards, Martínez-Mena et al. [35] measured a reduction of 85% in SL for techniques with green manure in inter-rows. Espejo-Peréz et al. [36] report that CC decreased SL in the olive orchard by an average of 76% in all experimental plots. The fact that all of these values are similar to our value points to the validity of our measurements. Significant reductions in total SL due to CC in inter-rows of permanent crops (but not in hop gardens) have also been previously reported by other authors [37–40]. However, some authors report considerable variability in SL. For example, Morvan et al. [41] report that if CC are degraded, the SL can be higher than in BS. Morvan et al. [41] also state that this was related to soil compaction and poor quality of

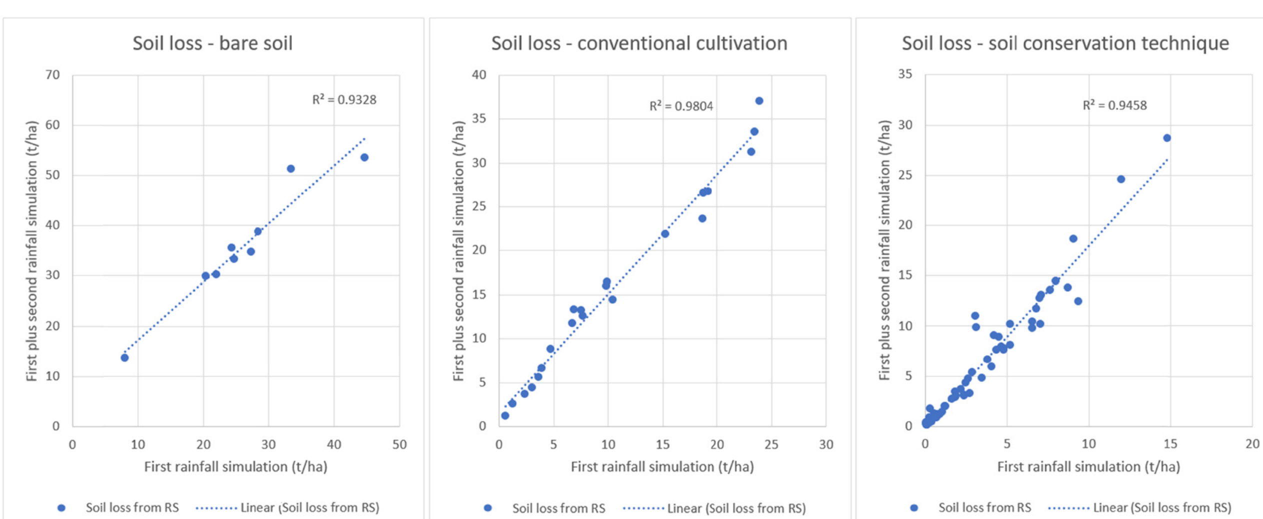

Figure 5: SL from individual rainfall simulator measurements from 2016 to 2023.

CC in the space of wheel tracks in the inter-row of vineyards. This is also the biggest limitation of SCT in hop gardens, because there is the degradation of the soil structure due to excessive soil compaction in the space of the wheel tracks, which is associated with frequent agrotechnical operations [42–44] and leads to increased bulk density [45]. The vegetation is damaged in this place, and in the event of torrential rainfall, surface runoff and water erosion begin there. This was also clearly visible in the RS. The solution could be local loosening of only compacted space, which increases the infiltration capacity of the soil and at the same time allows to use of CC in inter-rows of hop gardens [46]. However, the local loosening needs to be repeated during the season as the soil in this area will compact again over time.

4 Conclusion

The aim of the article was to determine the SL in hop gardens based on the measurements by the field rainfall simulator and then to calculate the C-factor, which is one of the factors of the Universal Soil Loss Equation. The SL is a variable value throughout the year, and therefore, several cropstage periods were verified. The mean SL for three cropstage periods (I, II, and III) from RS for CT was set at 0.81. The resulting C-factor is then 0.73. These values are very high and indicate an insufficient soil conservation of hop gardens when there is CT. The results also confirm that if the hop garden is located on a slope, severe water erosion can occur during torrential rainfall. In the case of SCT, the average SL from the RS (0.29) and C-factor (0.16) were significantly lower. CC in the inter-row thus appears as a potential solution for erosion-prone hop gardens. The stated results extend the area of research on water erosion and soil degradation in hop gardens, where there is currently a lack of information in the scientific literature.

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Conflict of interest: Authors state no conflict of interest.

Data availability statement: The datasets generated and analysed during the current study are available in the Research Institut for Soil and Water Conservation at Prague. They are also available from the corresponding author on reasonable request.

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4.3 Čirok (*Sorghum bicolor* (L.) MOENCH)

Čirok patří mezi obilniny pěstované především v teplejších oblastech světa. V posledních letech však získával stále větší pozornost i v podmínkách střední Evropy. Rostlina je ceněna zejména pro svou dobrou odolnost vůči suchu a schopnosti efektivně hospodařit s vodou. Výsledkem je stabilnější produkce biomasy v méně příznivých klimatických podmínkách. Čirok je využíván jako plodina potravinářská, krmná i energetická. Svým vzhledem a agrotechnickým způsobem pěstování se podobá kukuřici seté.

Z pohledu pěstitelských nároků se čiroku nejlépe daří na lehčích až středně těžkých půdách s dobrým provzdušněním a dostatečnou zásobou živin. Ve srovnání s kukuřicí má čirok nižší nároky na vláhu vzhledem k hlubšímu kořenovému systému a schopnosti omezovat transpiraci v období stresu. Díky těmto vlastnostem byl v minulosti často označován jako plodina s velkým potenciálem, respektive jako plodina budoucnosti. Své využití nachází i při ekologickém způsobu hospodaření. Za nevýhodu ve srovnání s kukuřicí lze považovat obecně nižší celkové výnosy a horší stravitelnost v případě, že je čirok využit jako krmivo pro hospodářská zvířata.

Podobně jako u kukuřice seté je možné čirok pěstovat pomocí celé řady agrotechnických postupů. Konvenční technologie spočívá v pěstování čiroku v řádcích, jejichž vzdálenost je 75 cm. Využít lze také technologii úzkého řádku (37,5 cm) nebo různé půdoochranné technologie. Z tohoto pohledu představuje čirok v podmínkách České republiky perspektivní plodinu vhodnou pro udržitelný způsob hospodaření.

V **Publikaci 6** je konkrétně popsána prozierozní účinnost u půdoochranné technologie založené na bezorebném setí (no-till) čiroku do porostu předplodiny. Dále bylo ověřeno konvenční zpracování půdy s klasickou roztečí řádků 75 cm společně s variantou úzkého řádku 37,5 cm. Široký a úzký řádek byl založen i u půdoochranného bezorebného setí čiroku.

Publikace 6

Název

Influence of No-Till Technology on Reducing Soil Degradation During Sorghum Cultivation

Citace

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INFLUENCE OF NO-TILL TECHNOLOGY ON REDUCING SOIL DEGRADATION DURING SORGHUM CULTIVATION*

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Soil degradation and water erosion are undoubtedly serious global problems. Moreover, excessive surface runoff and the lack of water in landscape are problems encountered not only in the Czech agricultural land. This condition is unsustainable in the long-term and it is necessary to find, verify and quantify suitable agricultural methods for reducing soil degradation. In this study, we tested two soil conservation technologies for sorghum (*Sorghum bicolor*) cultivation. Our results show that erosion was reduced by more than 78% (no-till) and 89% (no-till: narrow row) in rainfall simulation on naturally moist soil compared to conventional cultivation. Also, the use of conservation technologies reduced surface runoff (52% no-till, 68% no-till: narrow row). Sorghum has similar agronomic requirements as maize but it has the advantage of a good dryness tolerance and a high water use efficiency. The two-year research (2014, 2017) took place in the Central Bohemian Region. Soil degradation was verified using a rainfall simulator. The results have shown that both no-till technologies have a significant ($P < 0.05$) soil conservation effect.

soil conservation technology, soil loss, surface runoff, rainfall simulator, water erosion

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INTRODUCTION

Soil loss and insufficient water infiltration in agriculture are one of major worldwide problems (Boardman et al., 1990; Novara et al., 2011). In the Czech Republic more than 51% of agricultural land is threatened by soil degradation (Sarapatka, Bednar, 2015). Rainfall-induced soil erosion risk is especially high during summer storms or the early wet season, when plant cover is low (Taguas et al., 2015). As a result, there is excessive surface runoff, soil erosion and smaller fertility. Soil loss and surface runoff are increased especially due to soil management and tillage practices (Blavet et al., 2009; Vanwalleghem et al., 2011). Indeed, there are several reasons: conventional plowing, removal of the original vegetation, use of pesticides and herbicides that damage biological activity in soils (Pelosi et al., 2013), low overall vegetation cover, soil compaction due to machinery traffic (Tarolli et al., 2014), organic matter loss (Kabelka et al. 2019), and absence of soil erosion control measures (Arnaez et al., 2015). Therefore, there is a need to find soil conservation technologies that will make agriculture sustainable.

The crop which significantly contributes to water erosion and surface runoff is sorghum (*Sorghum bicolor*). Sorghum is globally the fifth most important cereal in terms of acreage and production (Beta, Corke, 2004). The main reason for sorghum high erodibility is insufficient soil conservation during the entire year. The bare surface is affected by intense

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storms that induce severe water erosion and runoff processes (Borga et al., 2011). Sorghum has a great drought tolerance and requires minimum fertilization on agriculture lands (Dicko et al., 2006). In the Czech Republic, maize is the most cultivated agricultural crop, but the advantage of sorghum compared to maize is a significantly lower need for water. The weather is becoming more extreme and there is a potential for sorghum cultivation in the conditions of the Czech Republic. Currently there are several kinds of soil conservation technologies for sorghum, but their evaluation needs further research.

The beneficial effects of soil conservation technology can be summarized as follows: (1) higher water retention in landscape (Cook et al., 2006; Mulumba, Lal, 2008), (2) protection of soil against raindrop impact, reducing erosion rates (Sadeghi et al., 2015), (3) decreased sediment and nutrient concentrations in runoff (Gholami et al., 2013), (4) decreased runoff generation rates and surface flow velocity by increasing roughness (Cerda, 2001), (5) improved infiltration capacity (Wang et al., 2014), (6) increased activity of some species of earthworms and microorganisms (Wooldridge, Harris, 1991), (7) enhanced soil physical conditions such as soil structure and organic content (Jordan et al., 2011; Karami et al., 2012), (8) reduced topsoil temperature for more optimum germination and root development (Dahiya et al., 2007) and decreased evaporation (Uson, Cook, 1995).

One kind of conservation technologies is the no-till technology which we tested in our research. The basic principles of no-till agriculture include the following: growing crops without using traditional tillage, retaining surface residue that reduces erosion, sowing directly into the soil covered by residue mulch. In addition to erosion control, no-till also saves energy (Javurek et al. 2007; Vach et al. 2016). Other types of soil conservation technologies are e.g. strip-till or cover crops (Brant et al., 2017). In some cases, afforestation can be a possible way to improve degraded soil. Afforestation of agricultural lands constitutes a serious change in soil dynamics (Holubik et al., 2014; Podrazsky et al., 2016) and it has a positive influence on physical characteristics of soil (Podrazsky et al., 2015).

MATERIAL AND METHODS

The two-year research took place close to the villages Krásná Hora nad Vltavou (in 2014) and Petrovice (in 2017) located in the Central Bohemian Region. Typical climate is slightly warm and dry. The terrain of wider surroundings is rugged. Soils were classified as Haplic Cambisols (Nemecek et al., 2011).

In our research focused on water erosion, surface runoff and infiltration we tested five soil conservation technologies: (1) control – bare soil, when the experimental plot was left completely without plant cover (Wischmeier, Smith, 1978); two technologies of conventional cultivation: (2) growing crops in 0.75 m wide rows (like in maize) and (3) narrow-row cultivation in just 0.375 m wide rows; and two technologies of no-till cultivation (growing crops without using traditional tillage and sowing directly into the soil covered with a residue mulch): (4) with a seeder specifically designed to cut through the residue and sow seed in 0.75 m wide furrows and (5) narrow-row cultivation in 0.375 m wide rows. By the no-till cultivation, the pre-crops were *Phacelia tanacetifolia* in 2014 and *Secale cereal* in 2017.

The plots suitable for the technologies verification were selected particularly for their slope uniformity – around 12% (Petrovice) and 8% (Krásná Hora nad Vltavou). The verification and check of selected technologies took place at three developmental stages of the crop cover. The plots were 20 m long and 7 m wide. The experimental plots with sorghum were established in three replications because of three terms. For this reason, unique rainfall simulations for each technology type in each term could be carried out. Overall, for each technology, there were six simulations of rainfall within the two years. The terms were determined according to the guidelines Erosion control in the Czech Republic – A handbook (Janecek et al., 2012). The individual measurement terms are defined below.

Term I (the second growing period). The period from plot preparation for sowing up to one month after sowing or planting. At the end of the second growing period the plant height was the following: conventional cultivation – 30 cm; conventional cultivation: narrow-row – 30 cm; no-till cultivation – 14 cm; no-till cultivation: narrow-row – 14 cm.

Term II (the third growing period). The period for the duration of the second month from spring or summer sowing. Before rainfall simulation the plants of sorghum had the following height: conventional cultivation – 210 cm; conventional cultivation: narrow-row – 215 cm; no-till cultivation – 110 cm; no-till cultivation: narrow-row – 100 cm.

Term III (the fourth growing period). The period from the end of the third period up to harvest. The plants under the used technologies had the following height: conventional cultivation – 240 cm; conventional cultivation: narrow-row – 240 cm; no-till cultivation – 200 cm; no-till cultivation: narrow-row – 200 cm.

The soil erosion and runoff processes were measured using a rainfall simulator. The measuring principle is based on rainfall simulation on a clearly defined and designated area. The size of the rainfall simulation area was 21 m^2, from which the surface water subsequently flowed along with eroded soil particles. During the rainfall simulation the surface runoff samples were always taken at the place of outflow into a calibrated container (319 ml volume). Sampling took place every three minutes with the aim to gather the total amount of eroded particles. After the simulation, each sample was oven-dried (Memmert UFB 400; Memmert, Germany) for 12 h at 105 °C under laboratory conditions. The amount of eroded undissolved particles for the particular technology was determined from the samples adjusted in this way. The total amount of eroded sediment from the verified area can be calculated by multiplying the average amount of undissolved particles in one sample and the size of surface runoff. Soil loss was assessed based on summary statistics for the used technologies. To test for difference in soil loss, the F-test and consequently t-test ($P < 0.05$) were used. The rainfall simulator allows for monitoring the erosion effect, but also the beginning and the end of surface runoff or the soil infiltration ability. The infiltration was determined based on the total amount of water and surface runoff captured during the simulation. The measured values included an error line segment describing the deviation in the measurements during the season.

The rainfall simulation provided a comprehensive set of information on the selected technologies and their soil conservation effectiveness during the time of torrential rainfalls. During the verification process the soil and slope conditions of the individual options must be as much similar as possible. Therefore the technologies were used and verified in the same place.

The rainfall simulation was carried out in two consecutive repetitions. The first rainfall simulation took 30-minute followed by a 15-minute technological break. Then the second (repeated) 15-minute rainfall simulation took place. The two rounds of rainfall simulation were selected in order to simulate rainfall on naturally moist soil and subsequently on already water-saturated soil. As for the rain simulator, the rainfall intensity was set at 60 mm/h. The conditions stated by Janecek et al. (2012) were taken into account when setting the rainfall simulation regime. This intensity was chosen based on the recommendation of the Czech Hydrometeorological Institute and it reflects the average intensity of torrential rainfalls in the Czech Republic.

RESULTS

Soil loss and surface runoff are related to bare soil, which was regarded as the control technology. Although the same method was applied during the simulation, it is not possible to compare the results for individual terms without converting them into a percentage expression. This is caused by the fact that during the technologies verification the soil moisture and temperature parameters may differ. For this reason the presented graphs are expressed in percentage, where the bare soil is considered the basis. In this way the individual terms during one year could be compared.

Rainfall simulation outcomes

Term I. The values measured during the rainfall simulations on naturally moist soils and already saturated soil are shown in Figs. 1 and 2. The worst results of soil loss were measured by the conventional cultivation (naturally moist soil 66.1%; already saturated soil 57.2%). As early as during the first term, a positive effect on soil conservation was observed in both no-till technologies. Soil loss was lower more than one-third compared to conventional cultivation. The surface runoff was reduced as well. The best values were achieved by the technology no-till: narrow row. The surface runoff was lower on naturally moist soil by 61.2% compared to conventional cultivation. Equally, the technology conventional cultivation: narrow-row achieved positive results but the difference was not so significant.

Term II. The influence of no-till technologies on reducing soil loss was clearly apparent also in the second term of simulation. The measured values

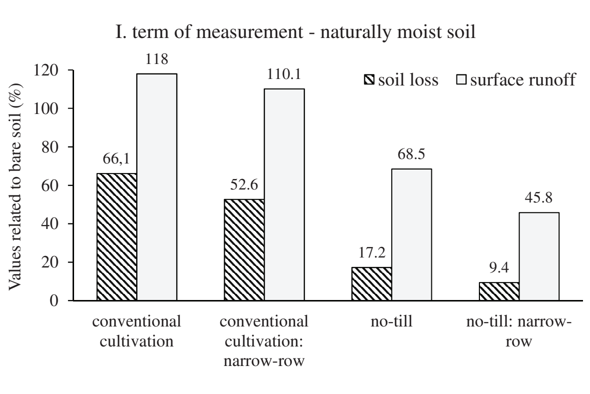

Fig. 1: The average relative values of soil loss and surface runoff from all rainfall simulations in the first term (30-minute-simulation)

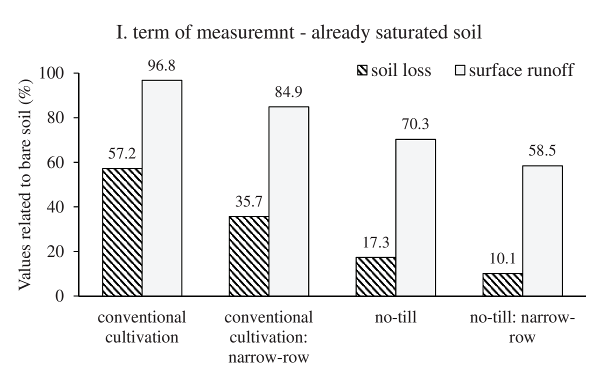

Fig. 2: The average relative values of soil loss and surface runoff from all rainfall simulations in the first term (15-minute-simulation)

were similar in character to those in term I but the differences in the total soil loss between bare soil and other technologies were higher. For example, no till: narrow row technology showed the soil loss only 0.8% related to bare soil. Excessive surface runoff showed the technology of conventional cultivation (naturally moist soil 94.3%; already saturated soil 93.3%). No-till technologies (no-till, no-till: narrow row) reduced surface runoff compared to conventional cultivation in both simulations. No-till: narrow row showed by 81.3% lower surface runoff during the simulation on naturally moist soil compared to conventional cultivation. The amount of soil loss and surface runoff during rainfall simulations is depicted in Figs. 3 and 4.

Term III. There was a still lower soil loss by both no-till technologies in the third term. The character of soil loss was again very similar to that in the previous two terms. The exception was no-till technology in the second simulation on already saturated soil where there was a low difference between conventional cultivation and no-till technology (10.4%). The values of surface runoff were positive in no-till technologies. The best value was measured in no-till technology on naturally moist soil (surface runoff by 96% lower compared to conventional cultivation). By the remaining two technologies there was an excessive surface runoff (conventional cultivation, conventional cultivation: narrow row). The results from rainfall simulations are presented in Figs. 5 and 6.

Research results evaluation

A characteristic feature of soil conservation technologies (including no-till technologies) during cultivation is retaining the residues of biomass on the soil surface (Alberts, Neibling, 1994). Bare soil, being considered the worst option, was chosen as the control plot to which the outcomes of the other used technologies were related. Surface runoff results of conventional cultivation do not differ much from those in bare soil. This fact points out to insufficient soil conservation efficiency of the traditional way of farming. Likewise, soil loss is high by the technology of conventional cultivation. Both no-till technologies (no-till and no-till: narrow row) provide much better results in all measuring characteristics compared to

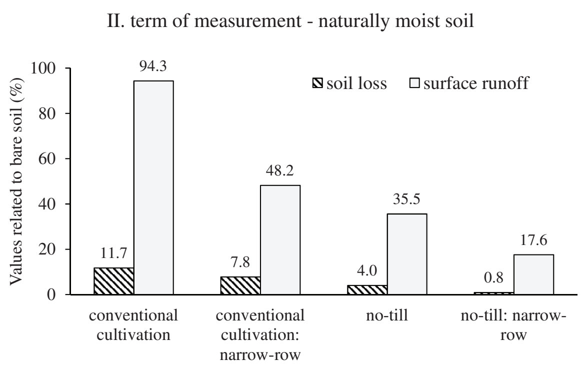

Fig. 3: The average relative values of soil loss and surface runoff from all rainfall simulations in the second term (30-minute-simulation)

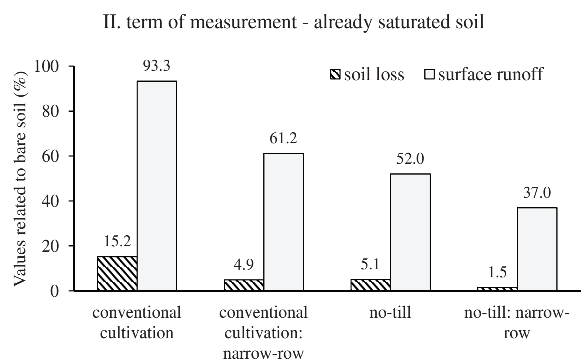

Fig. 4: The average relative values of soil loss and surface runoff from all rainfall simulations in the second term (15-minute-simulation)

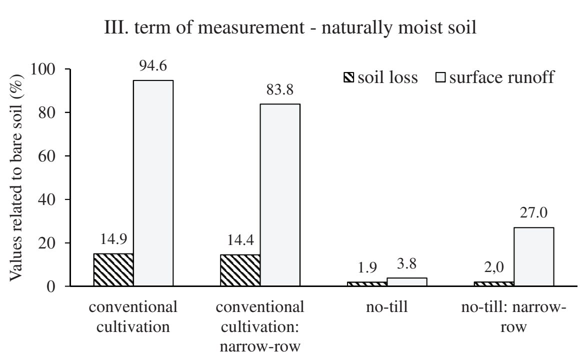

Fig. 5: The average relative values of soil loss and surface runoff from all rainfall simulations in the third term (30-minute-simulation)

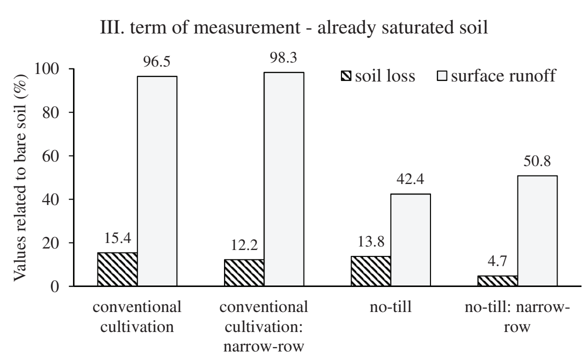

Fig. 6: The average relative values of soil loss and surface runoff from all rainfall simulations in the third term (15-minute-simulation)

Table 1. Average values from three terms of rainfall simulation measurements in the seasons 2014 and 2017

Type of technology		Surface runoff		Soil loss	
		(mm)	(%)	(t ha^{-1})	(%)
Naturally moist soil (30-min simulation)	bare soil	18.13	100	11.13	100
	conventional cultivation	16.48	90.92	3.52	31.6
	conventional cultivation: narrow-row	14.74	81.3	2.77	24.9
	no-till	7.82	43.15	0.75	6.69
	no-till: narrow-row	5.14	28.35	0.38	3.4
Already saturated soil (15-min simulation)	bare soil	10.7	100	4.54	100
	conventional cultivation	9.98	93.27	1.46	32.09
	conventional cultivation (narrow-row)	8.64	80.78	0.88	19.27
	no-till	6.37	59.5	0.57	12.44
	no-till: narrow-row	5.36	50.11	0.26	5.69

Table 2. Basic statistical parameters of soil loss

Basic parameters	Conventional cultivation	Conventional cultivation: narrow row	No-till	No-till: narrow row
Mean	2.487	1.823	0.655	0.318
Variance	7.549	4.58	0.711	0.229
Observations	12	12	12	12

Table 3. *F*-test for soil loss values

Technology	Conventional cultivation	Conventional cultivation: narrow row	Conventional cultivation	No-till	Conventional cultivation	No-till: narrow row
Degree of freedom	11		11		11	
F-test value	1.648		10.622		32.988	
P-value 0.05 (one-tail)	0.21		2.37E-04		8.13E-07	
F-test critical value (one-tail)	2.818		2.818		2.818	

conventional cultivation. Erosion was reduced by more than 78% (no-till) and 89% (no-till: narrow row) in the rainfall simulation on naturally moist soil compared to conventional cultivation. In the case of rainfall simulation on already saturated soil erosion was reduced by 61% (no-till) and 82% (no-till: narrow row). The surface runoff in conservation technologies compared to conventional cultivation was reduced as follows: naturally moist soil – 52% (no-till) and 68% (no-till: narrow row); already saturated soil – 36% (no-till) and 46% (no-till: narrow row). Conventional cultivation: narrow row also showed in most cases better results, but the soil conservation effect was not so high. The average values from all measurements are summarized in Table 1. For soil loss results we determined basic statistic parameters, *F*-test and *t*-test (Tables 2–4). The outcomes show that the values for no-till technologies are statistically different ($P < 0.05$) from those for conventional cultivation.

In this study, we further evaluated the infiltration process during rainfall simulation. A lower surface runoff from plots means a higher infiltration. The measured values are given in Figs. 7 and 8. In the rainfall simulation on naturally moist soil, the infiltration was higher by 8.68 mm in no-till technology and by 11.37 mm in no-till: narrow row technology compared to conventional cultivation. Also, infiltration was the highest in no-till technologies on already saturated soil.

DISCUSSION

The study results are among the first to provide information on the soil conservation efficiency of no-till technologies during sorghum cultivation under the conditions of the Czech Republic. The most important outcomes of this research concern the rate of water

Table 4. *t*-Test for soil loss values

Technology	Conventional cultivation	Conventional cultivation: narrow row	Conventional cultivation	No-till	Conventional cultivation	No-till: narrow row
	two-sample assuming equal variances		two-sample assuming unequal variances		two-sample assuming unequal variances	
Pooled variance	6.065		x		x	
Hypothesized mean difference	0		0		0	
Degree of freedom	22		13		12	
t-Test value	0.66		2.208		2.693	
P-value 0.05 (one-tail)	0.258		0.023		0.01	
t-Test critical value (one-tail)	1.717		1.771		1.782	
P-value 0.05 (two-tail)	0.516		0.046		0.02	
t-Test critical value (two-tail)	2.074		2.16		2.179	

erosion, surface runoff and infiltration when applying the conventional cultivation and no-till technologies. Based on our evaluation, it is apparent that no-till has a significant ($P < 0.05$) impact on soil conservation. On the contrary, the values measured in conventional cultivation show insufficient soil conservation before degradation. Blanco, Lal (2010) stated that the main cause of erosion and excessive surface runoff on the plots is a low soil cover. In this study we have arrived to the same conclusion. Erosion and surface runoff are much higher by conventional cultivation where there is no vegetation cover.

A direct correlation between erosion and soil management has been found by many authors (Shipitalo, Edwards, 1998; Javurek et al., 2008). Soil conservation technologies have been recognized as effective methods for controlling soil erosion (Lal et al., 2007). According to Wendt, Burwell (1985) erosion was reduced by more than 90% in the case of soil conservation technologies leading to a significant reduction of soil degradation processes. Strauss et al. (2003) analyzed 68 studies with 160 comparable results where soil erosion and surface runoff were determined under different soil tillage practices. On the average, soil conservation technologies have reduced soil erosion by 60% (arithmetic mean) and 76% (median). For the no-till technology Prashun (2012) stated a 90.3% reduction in erosion. Nyakatawa et al. (2001) estimated that the no-till technology reduces soil erosion by water by 75% compared to conventional tillage. Basically, our results are similar to those given by other researchers. A comparable research with sorghum was carried out by Gilley et al. (1986). From this research it is obvious that the

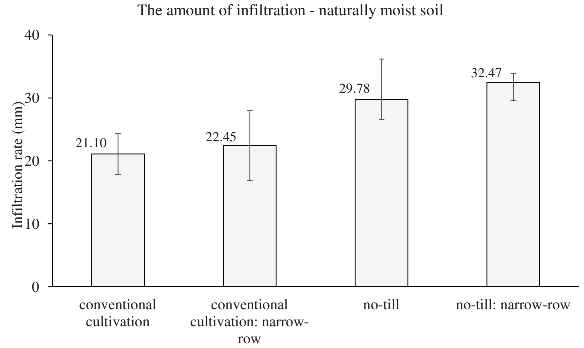

Fig. 7: Infiltration during the season from years 2014 and 2017 (30-minute-simulation)

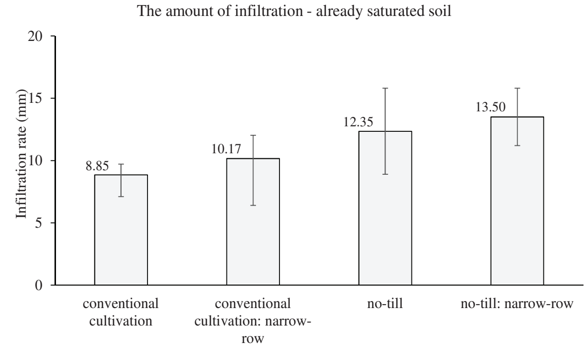

Fig. 8: Infiltration during the season from years 2014 and 2017 (15-minute-simulation)

higher the amount of residuals on the surface, the lower the soil loss and the surface runoff. In a similar way McGregor, Mutchler (1992) associated the degradation processes with the conservation tillage and no-till technology for sorghum. In no-till technology for sorghum the soil loss was reduced by 97% and the surface runoff was reduced by 44% compared to conventional cultivation. The values stemming from our rainfall simulation are from a two-year research and a certain dispersion cannot be excluded, however, there is only a little presumption of significant changes in the measured results.

CONCLUSION

The issue of soil loss and excessive surface runoff accompanying the conventional cultivation of sorghum is highly important. The results obtained in our study indicate that growing sorghum in erosion prone areas requires application of a different agricultural method. The rainfall simulation results show that the final soil loss caused by water erosion and surface runoff can be quite effectively reduced by using the no-till technology. During the season, the amount of soil loss in plots with no-till technologies was reduced to a minimum compared to conventional cultivation (by more than three-quarters in naturally moist soil). Similarly, the amount of surface runoff was reduced in plots with no-till technologies. The most prone period is the time after seeding because the plant cover is low. Nevertheless, the no-till technology shows a soil conservation effect even in the first stage. Thus, in the period of most frequent torrential rains the no-till technology prevented soil erosion. Due to the fact that soil erosion and surface runoff were lower by the soil conservation technologies compared to the conventional cultivation in all realized measurements, it can be concluded that the no-till technology significantly ($P < 0.05$) reduced soil loss and surface runoff.

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4.4 Brambory (*Solanum tuberosum* L.)

Brambory jsou řazeny mezi nejvýznamnější zemědělské plodiny mírného pásma. V České republice mají dlouholetou pěstební tradici. Jsou ceněny pro svůj vysoký výnos a široké využití: potravinářství, krmivářství či průmysl. Hlízy brambor díky obsahu škrobu, vitamínu C a dalších minerálních látek představují důležitý zdroj energie a živin. Z hlediska pěstitelských nároků vyžadují brambory kvalitní a dobře provzdušněnou půdu pro správný vývoj hlíz. Z hlediska zrnitosti půdy jsou pro ně optimální lehké až středně těžké půdy s dostatkem organické hmoty. Brambory dobře reagují na hnojení pomocí organických hnojiv. Významným faktorem je dále vláhový režim půdy, protože jsou náchylné na výraznější sucho, ale i na přemokření (tvorba plísní).

Pěstování brambor je spojeno s tvorbou brázd a hrůbků. Díky tomuto technologickému postupu jsou brambory řazeny mezi širokořádkové plodiny. U konvenčního technologického způsobu pěstování (pravidelné hrůbky, případně tzv. dvojhrůbky) je riziko vzniku erozní události vysoké. Proto je v případě brambor snaha uplatňovat půdoochranné technologie. Nejčastěji se jedná u různé úpravy v prostoru hrůbků a brázd. Za tyto úpravy lze považovat důlkování a hrázkování hrůbků, ukládání kamenů do kolejové brázdy (odkameňování) či různé kypření půdy. V rámci těchto úprav však není zvyšována pokryvnost povrchu půdy rostlinnými zbytky. S tím souvisí výsledná protierozní účinnost. Při srovnání s technologiemi no-till či strip-till, které jsou určeny například pro pěstování kukuřice, je protierozní účinnost u výše zmíněných úprav hrůbků a brázd výrazně nižší.

Určitým řešením by mohlo být pěstování brambor s pomocnou plodinou zasetou v prostoru brázd. Díky přítomnosti pomocné plodiny je půda v tomto prostoru více chráněna v důsledku přítomnosti kořenů a stejně tak je zvýšena celková pokryvnost povrchu. Technologie pěstování brambor s pomocnou plodinou není prozatím v České republice příliš rozšířena, přestože je protierozní účinnost u této technologie výrazněji vyšší než v případě pouhé úpravy tvaru hrůbků a brázd. Podrobnější výsledky jsou uvedeny v **Publikaci 7**.

Publikace 7

Název

Different technologies of potato (*Solanum tuberosum* L.) cultivation and their effects on water runoff and soil erosion.

Citace

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Different technologies of potato (*Solanum tuberosum* L.) cultivation and their effects on water runoff and soil erosion

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Abstract: Surface runoff and soil losses in the case of potato cultivation using de-stoning technology on gentle slopes (Haplic Cambisol) were studied in 2020–2022. Different ridges shapes were compared: control (smooth shaped ridges), pits, pits plus loosening, pits plus loosening plus cover crop (*Triticum aestivum* L.) sowing in trail furrows. Runoff and soil losses were studied approximately 1 and 2 months after planting potatoes. The obtained results showed the highest reduction of surface runoff and soil losses in the treatment with cover crop sowing. In this variant, soil losses were reduced by 65–81% (1 month after planting) and 54–85% (2 months after planting) in case of simulated rainfall on the soil with natural moisture (or these losses were reduced by 51–93% and 50–76% in case of 15-min rainfall). On average, tuber yields reached 29.4 t/ha (pits + loosening) to 30.6 t/ha (pits) in 2020–2022. The different abilities of the tested shapes of ridges and furrows to retain water did not significantly affect the achieved yields of tubers, as rainfall was not a limiting factor in the monitored period. The yield differences among all tested treatments reached units of tons per hectare if the entire dose of nitrogen was applied at planting. Splitting the total nitrogen dose (50% at planting, 50% at loosening) gave significantly ($P < 0.05$) higher yields (34.2 t/ha) than a single application at planting. The treatment pits plus loosening with fertilisation provided a 19–26% higher tuber yield than pits plus loosening with a total N dose applied at planting.

Keywords: crop canopy; erodibility; fertiliser; water retention; wheat

More than 50% of agricultural land is threatened by water erosion (and approximately 10% by wind erosion) in the Czech Republic; also, 5–10% of forest soils are damaged by water erosion etc. For example, healthy forests usually protect soils from erosion; the network of forest roads, including skid trails, was shown to alter hydrological processes and cause soil erosion by water (Zemke 2016). Concerning soil erosion, the cultivation of potatoes is problematic. Potato cultivation may lead to water and wind (and tillage and harvest) erosion (e.g., Chow and Ress 1994, Sharratt and Colins 2018, Nyawade et al. 2019,

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Lemann et al. 2019, Edwards et al. 2020). For example, Chow and Ress (1994) studied the effect of hilling (*Solanum tuberosum* L.) on surface runoff, infiltration and soil erosion using a rainfall simulator (hilled versus unhilled plots). The authors state that the use of hilling caused higher runoff (mean runoff rate was 20% higher), lower infiltration (30% lower) and approximately four times higher soil losses compared with unhilled plots. Nyawade et al. (2018) studied sediment particle size distribution and soil organic matter losses (including soil organic matter fractions) in the case of potatoes intercropping with different legumes. Concerning potato intercropping, see Ren et al. (2019), Zhang et al. (2020), etc. To reduce soil erosion during potatoes cultivation (slow emergence), Jemison (2019) tested nurse crops, including seeding rates, duration and the use of herbicides before incorporation into the soil. Partitioning of rainfall by crop canopies (interception, throughfall and stem flow) may influence erosional processes (Ma et al. 2013, 2015). Janeau et al. (2015) studied stem flow in the case of different plants, including *Solanum tuberosum* L. (the stage of potatoes growth = maturity). Concerning potatoes, the authors found that stem flow formed 30% of total simulated rain at an intensity of 27 mm/h (and 15% of rain at an intensity of 70 mm/h). Saffigna et al. (1976) used a tracer (Rhodamine WT) to study infiltration in the case of *Solanum tuberosum* L., cv. Russet Burbank; for example, the authors state that stem flow increased water content around the stems. Albedo of potato fields was found to be 9–21%; for example, the values 13–25% (wheat) and 14–36% (barley) were reported in different publications (e.g., Tajchman 1971, Piggin and Schwerdtfeger 1973). Also, Aksic et al. (2014) showed the effect of matric potential (or water consumption for evapotranspiration) on potato yields etc. (Kang et al. 2004).

Concerning potatoes cultivation, increasing potatoes yields per hectare and decreasing the area of potatoes cultivation in the Slovak Republic (the period from 1950 to 2017) are described in Koco et al. (2020). The authors also state different soils on which potatoes are cultivated (Cambisols – 28% of the potato cultivation areas, Chernozems – 20%, Fluvisols – 18%, Dystric Planosols – 11%), including texture, the content of gravel, depth, slopiness. According to Koco et al. (2020), 26% of the areas are in the Slovak Republic's very warm, very dry climatic region (and 14% in a very cold, wet climatic region).

Potatoes are grown almost exclusively in technology with de-stoning in the traditional potato-growing region of the Czech Republic. Furrowing and namely stone and clod separation causes intensive soil aeration and mineralisation of organic matter; therefore, this technology highly demands returning organic matter to the soil. Cattle manure is usually ploughed in autumn, mineral fertilisers (P, K) are continuously applied in the spring before de-stoning, and nitrogen fertilisers when planting directly into ridges. Placement of fertiliser N in the ridges has a positive effect of N recovery in comparison with broadcast fertilisation, especially when the total amount of nitrogen is applied at planting (Maidl et al. 2002). The seed tuber is the primary nutrient and energy source for developing shoots during the first 30 days after planting, and soil N uptake is minimal. Between 30 and 55 days, roots begin to provide nutrients. Only about 20% of the crop N uptake occurs by the end of this period, and therefore high rates of fertiliser N applied prior to this stage may increase the risk of nitrate leaching and nitrous oxide emissions (Zebarth and Rosen 2007). Potatoes require large amounts of nitrogen over a relatively short period of rapid growth (lasting 30 to 50 days with a view to cultivar). As published by Kelling et al. (2015), the efficiency of applied nitrogen can be increased by splitting the in-season N applications and different ridge shapes. Modification of the ridge shape affects water infiltration into the ridge and soil moisture. Improving fertiliser nitrogen use efficiency is an opportunity, especially on sandy soil (Jordan et al. 2013).

In this study, we attempted to determine runoff and soil losses in the case of potato cultivation on gentle slopes with the use of different technologies, which are described below. We hypothesised that using technologies with treatment in both trail and non-trail furrows would lead to the highest reduction of runoff and soil losses (e.g., Vejchar et al. 2017). We also hypothesised a reduction of runoff (rather than soil losses), especially when the technologies with the restoration of pits in the non-trail furrow (at the beginning of emergence) will be used. The second question was whether the different shapes of ridges and more water retention affect the tuber yields achieved. There was a risk that the plants under the pits would be less profitable (than below the dams) due to the shallower planting of the tubers. The impact of cover crops in the trail furrow on the yield in the adjacent ridges was also studied. And finally, the effect of the different timing of nitrogen application on potato yield was observed.

https://doi.org/10.17221/149/2023-PSE

MATERIAL AND METHODS

The experiments were performed near Věž in Havlíčkův Brod district (the Bohemian-Moravian Highlands) in the Czech Republic (the years 2020–2022) – gentle slopes (Haplic Cambisol – IUSS Working Group WRB (2015), an average altitude = 605 m a.s.l.). This area is characterised by a mean annual air temperature of 5–6 °C and by a mean annual precipitation of 700–800 mm, and a sum of temperatures above 10 °C between 2 000 and 2 200 (mildly cold, wet climatic region of the Czech Republic) – from data obtained in the period 1950–2021.

The field experiments were established using destoning technology on sloping areas (4.51°, 3.94° and 4.86° in 2020, 2021 and 2022, respectively) with the orientation of the ridges following the fall line in all years. Mineral nitrogen, possibly phosphorus and potassium fertilisers were applied before grooving in April in the following way: NPK 15-15-15 300 kg/ha and ammonium sulphate 300 kg/ha (2020), UAN (urea and ammonium nitrate) 150 L/ha (2021), NP 20-20 200 kg/ha + ammonium sulphate 250 kg/ha (2022). Fertiliser doses were determined by the N_{min}, P and K content in the soil. The total nitrogen doses reached 105, 60 and 90 kg N/ha in 2020, 2021 and 2022, respectively. Planting (cv. Antonia) was realised using innovated planter Grimme GB 230 on May 6, 2020, May 12, 2021, and May 10, 2022. Four treatments were established (the size of individual plots = 900 m^2): (1) control (smooth shaped ridges); (2) pits (large pits and transversal dams on the top of ridge, transversal dams in non-trail furrow formed at planting); (3) pits plus loosening (the same as 2 plus loosening of ridges top and restoration of pits in non-trail furrow at the beginning of plants emergence with the possibility of in-season fertilisation); (4) pits plus loosening plus sowing (the same as 3 plus sowing of cover crop, *Triticum aestivum* L., and damming in the trail furrow). Fertiliser $UREA_{stabil}$ (80 kg N/ha) was applied on both tubers' sides in all planting treatments. Treatment 3 was established in two treatments: (3a) 80 kg N/ha at planting and (3b) 40 kg N/ha at planting plus 40 kg N/ha at loosening. Liquid fertiliser UAN was applied from the non-trail furrow to the ridge in the root zone of plants. Loosening of ridges top with the restoration of pits in the non-trail furrow (3a), possibly with in-season fertilisation (3b), and cover crop sowing and damming in the trail furrow (4) was carried out on May 27, 2020, June 7, 2021, and June 6, 2022. The pre-emergence herbicide (Planteen 41.5 WG) was always applied 1–2 days after planting. Applications of other herbicides (Arcade 880 EC, Agil) and fungicides against late blight were carried out regarding current needs and the prognosis of late blight occurrence in individual experimental years. Nine applications of fungicides in the sequence Ridomil Gold MZ Pepite (active substance: Mancozeb, Metalaxyl-M) 2×, Revus Top (a. s. Difenoconazole, Mandipropamid) 2×, Infinito (a. s. (Fluopicolide, Propamocarb hydrochloride) 2×, Vendetta (a. s. Azoxystrobin, Fluazinam) 1×, Ranman Top (a.s. Cyazofamid) 2× were carried out under conditions of strong fungal infection pressure in 2020 and 2021. Only seven applications (Revus Top 3×, Infinito 2×, Vendetta 2×) were needed in 2022. The insecticides Biscaya (Thiacloprid) (2020 only), Coragen (Chlorantraniliprole) and Spintor (Spinosad) were used against the potato beetle. Potato harvest (four plots per treatment) with a small plot harvester occurred on September 17, 2020, September 27, 2021, and October 10, 2022. The influence of different planting depths (under a pit or a dam) on tuber yield was determined by manually harvesting individual plants. Yield results were statistically evaluated by one-way analysis of variance and Tukey's *HSD* (honestly significant difference) test at the significance level ($P < 0.05$). Statistically, significantly different values are marked with different letters (a, b).

In 2020–2022, the rainfall simulations were realised approximately 1 month after planting (the first term) and 2 months after planting (the second term). The used field rainfall simulator (a size of rainfall simulation area = 21 m^2, the intensity of rainfall 1.2 mm/min) plus measurement principles are described in different publications (e.g., Kabelka et al. 2019, 2021, Kincl et al. 2021). All rainfall simulations were done twice consecutively (the first measurement = 30 min of simulated rainfall on the soil with natural moisture; after 15 min of technological break, the second 15-min rainfall simulation on the same and saturated soil). Statistical testing was realised with the use of a *t*-test.

RESULTS AND DISCUSSION

Rain simulations. In 2020 (approximately 1 month after planting), the soil losses were the lowest in the treatment with pits plus loosening plus sowing, pits or pits plus loosening (Figure 1). These losses were 65, 31 or 22% lower than the control treatment (the first rainfall simulation = the soil with natural

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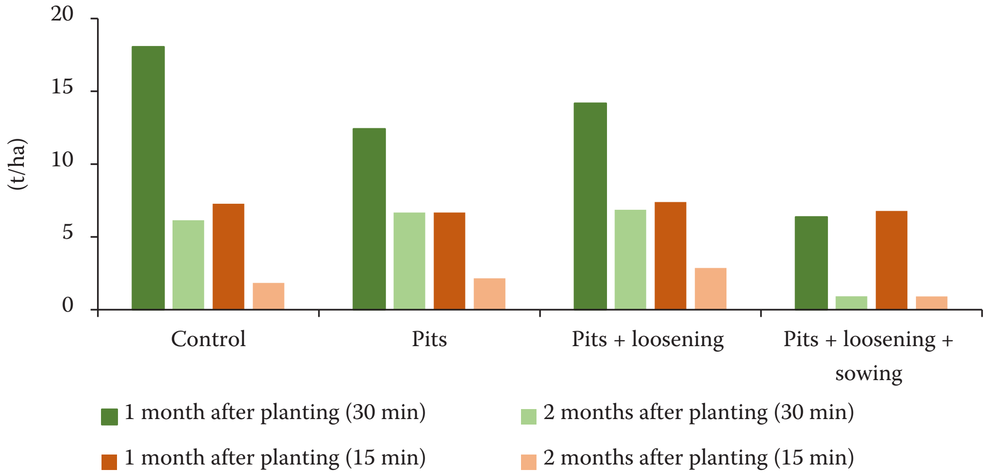

Figure 1. The values of soil loss in individual treatments of potato (*Solanum tuberosum* L.) cultivation in 2020

moisture, 30 min of simulated rainfall). Runoff values decreased by 31% (pits plus loosening plus sowing), 22% (pits plus loosening) or 4% (pits) compared with the control. Two months after planting (= the second term), the loss of soil was lower in the case of the treatment with pits plus loosening plus sowing (by 85%) compared with the control; in the other treatments (pits, pits plus loosening), soil losses were higher than those in the control treatment – the first rainfall simulation (30 min). The values of runoff decreased by 29% (pits plus loosening plus sowing), 18% (pits plus loosening), and 13% (pits). In the case of the second simulation (15 min), decreased losses of soil (by 50%) were in the treatment with pits plus loosening plus sowing; in the other treatments, soil losses were higher compared with the control (Figure 1). The runoff values decreased by 2% in the treatment with pits plus loosening plus sowing. In the treatment with pits plus loosening, the runoff values were the same as in the case of the control treatment; higher runoff values were found in the treatment with pits (15-min rainfall simulation).

In the year 2021 (1 month after planting), the soil loss was 19% (pits + loosening + sowing), 57% (pits) or 97% (pits + loosening) of the control (30 min of simulated rainfall) – Figure 2. The runoff decreased in all treatments by 18–35% (the lowest runoff = pits plus loosening). In the case of the second rainfall simulation (15 min), the soil loss was 49% (pits + loosening + sowing), 65% (pits) or 100% (pits + loosening) of the control (Figure 3). The runoff values also decreased in all treatments by 36–42% (the lowest

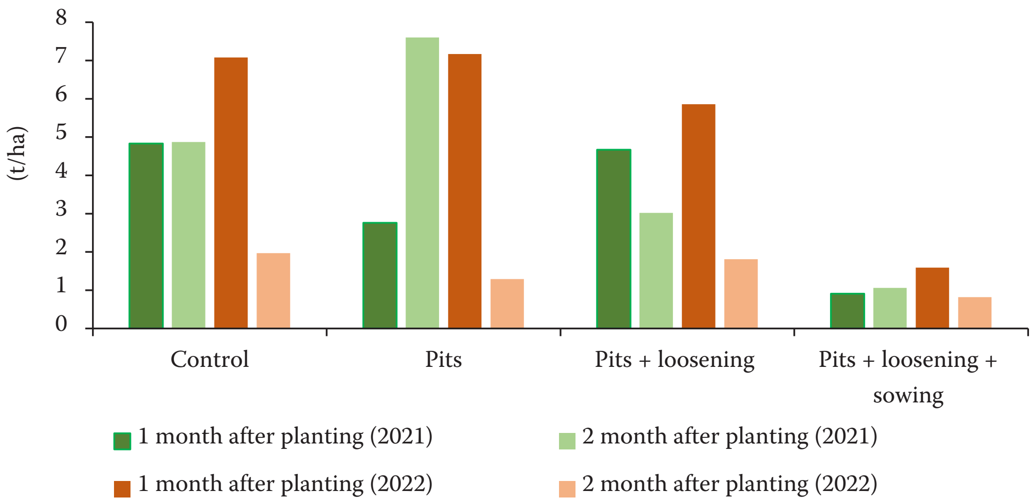

Figure 2. The values of soil loss in individual treatments of potato (*Solanum tuberosum* L.) cultivation in 2021 and 2022 (the first simulation = 30 min)

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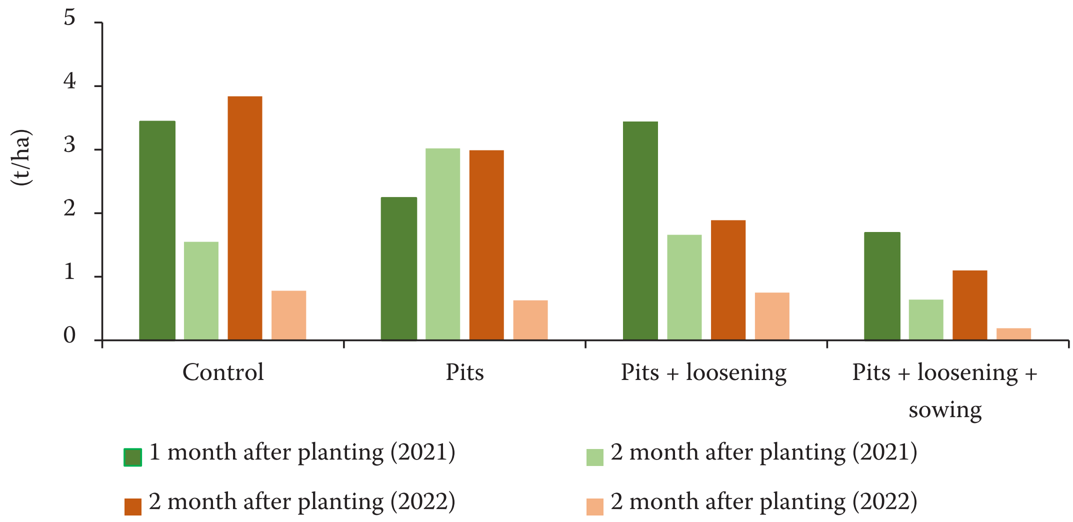

Figure 3. The values of soil loss in individual treatments of potato (*Solanum tuberosum* L.) cultivation in 2021 and 2022 (the second simulation = 15 min)

runoff = pits plus loosening). Two months after planting, soil losses decreased only in the case of pits plus loosening plus sowing (by 78%) or pits plus loosening (by 38%) – 30-min simulation; in the case of 15-min simulation, soil losses were 41% (pits plus loosening plus sowing), 107% (pits plus loosening) and 195% (pits) of the control treatment. Runoff decreased in all treatments (both 30-min and 15-min simulation) by 18–36% (the most efficient treatments = pits + loosening + sowing, pits + loosening).

In 2022 (1 month after planting), the value of soil loss was the lowest in the treatment pits + loosening + sowing (22% of the control); soil losses were similar in the control and treatment with pits (30-min simulation) – Figure 2. Soil losses decreased in all treatments and were the lowest in the case of pits + loosening + sowing (29% of the control) and pits + loosening (49%) (15-min simulation). The runoff values decreased by 22–27% (both 30-min and 15-min simulations). Two months after planting, the highest reduction of soil losses was found in the treatments pits + loosening + sowing (by 58%) and pits (by 35%) – 30-min simulation. Concerning the second rainfall simulation, the reduction was found in all treatments and was the highest in the case of pits + loosening + sowing (76%). The runoff values decreased by 10–24% (30 min of simulated rainfall), and the treatment pits were the most efficient. Concerning 15 min of simulated rainfall, the highest reduction was also found in the case of pits. Concerning the losses of soil (in the period 2020–2022), their significant ($P < 0.05$) reduction was found only in the case of the treatments with cover crop sowing (30-min and 15-min simulation); the values of runoff were significantly ($P < 0.05$) reduced in all treatments (30-min and 15-min simulation) – Table 1.

From all variants tested in 2020–2022, the highest reduction of surface runoff and soil losses was found in the variants with treatment in non-trail and trail furrows. In this variant, soil losses were reduced by 65–81% (1 month after planting) and 54–85% (2 months after planting) in case of simulated rainfall on the soil with natural moisture (or these losses of soil were reduced by 51–93% and 50–76% in case of 15-min rainfall). In the study by Vejchar et al. (2017, 2019), trail furrows formed larger areas in potato cultivation compared with non-trail furrows; higher runoff and soil erosion were in trail compared with

Table 1. *P*-values from statistical testing with the use of a *t*-test

	Soil losses		Runoff	
	30 min	15 min	30 min	15 min
Control versus pits	0.2503	0.3416	0.0008	0.0146
Control versus pits + loosening	0.0822	0.3882	0.0003	0.0282
Control versus pits + loosening + cover crop sowing	0.0076	0.0085	0.0017	0.0314

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non-trail furrows (the variants with and without tight ridging in trail plus non-trail furrows). Vejchar et al. (2017) compared variants with and without tight ridging (de-stoned soil, a 5% slope); renewal of dams in the tight ridged furrows (10 cm width, basins between them 40 × 25 cm) was performed 14 days after potatoes emergence. As stated by the authors, surface runoff (and soil erosion) were 78% (and 88%) lower in variants with tight ridging; surface runoff or soil erosion from trail furrows formed 58% of total runoff or soil erosion from the variants without tight ridging.

In this study, the treatments with the sowing of wheat (and damming) in trail furrows were the most effective; according to different authors, the use of wheat seems to be more effective in reducing soil losses rather than runoff (Lin et al. 2019, Kincl et al. 2022, etc.). Nyawade et al. (2019) realised a study (Kenya, Nitisols according to FAO) to find the effects of potatoes intercropping with different grain legumes on soil surface roughness, soil losses (and nutrient losses), runoff etc. For example, the authors state that the highest soil losses (and runoff) were found in the case of bare soil; the losses of soil (and runoff) were also higher in the case of pure potato stands (all stages of potato growth – emergence, vegetative, tuber initiation, postharvest) compared with the treatments with legumes. The authors also described higher soil organic carbon (and phosphorus, potassium etc.) export rate in the case of pure potato stands compared with the treatments with intercropping. For example, the use of intercropping improved the dissipative effect of the canopy on the kinetic energy of raindrops. The authors describe a decrease of surface roughness at potato emergence etc.; according to the authors, changes in surface roughness may be given by canopy development, rainfall intensity etc.

Vejchar et al. (2019) studied the effect of tight ridging on surface runoff (de-stoned soil, an 8.8% slope) and potato yields (reservoirs at 50-cm intervals, 2-L volume). The authors state that the use of tight ridging led to a reduction of surface runoff by 43–78% compared with the control. For example, Vejchar et al. (2019) mentioned that the filling of reservoirs (sediment) was more pronounced before the development of foliage; the authors recommended that the reservoirs can be restored before foliage development. It was stated by Vejchar et al. (2019) that the efficiency of tight ridging in trail furrows was lower compared with that in non-trail furrows; according to the authors, it was because of the same dimensions of reservoirs (trail and non-trail furrows) and larger areas of trail furrows in potato cultivation. Also, Vacek and Vejchar (2017) reported that soil losses in furrows or trail furrows were lower in the case of pits (with or without their renewal) compared with the control. Concerning this study, it is worth mentioning runoff reduction in the case of pits plus loosening. It is reduced by 22–35% (1 month after planting) and by 11–34% (2 months after planting) in case of 30-min rainfall; in case of 15-min rainfall, the runoff was reduced by 6–42% (1 month after planting) and 0–29% (2 months after planting).

Tuber yields. The potato tuber yields achieved were low (25.3–27.2 t/ha) due to the short vegetation season in 2020. The slow and long emergence of the crop during the cold and wet month of May and the early termination of the vegetation season due to the strong attack of the late blight were the causes. The ridges shape, cover crop in furrow, or nitrogen doses splitting did not significantly affect tuber yields. The smooth control ridge yielded 26.5 t/ha. The other treatments were at the level of 95–103% of the control (Figure 4A). The results achieved in 2021 and 2022 were similar (Figures 4B and 4C). No significant differences in tuber yields were found between the treatments with applying the total nitrogen dose at planting. They reached 32.2–32.8 t/ha and 30.2–32.1 t/ha for these treatments and were at the level of 100–102% and 98–104% of control in 2021 and 2022, respectively. The highest yields of tubers (39.0 and 38.1 t/ha in 2021 and 2022, respectively) were found in the treatment with pitting and fertilisation during loosening at the beginning of stand emergence (treatment 3b). They achieved 121% and 124% of control, respectively, and were statistically significantly higher from all treatments with nitrogen application at planting only.

The high amount of precipitation (86–98 mm) between planting and fertilising at the beginning of plant emergence (3–4 weeks) was probably the cause. Nitrogen applied at planting may have been washed away from the plant roots before the plants took it up. This is also confirmed by the results of field experiments with fertilisers labelled with the ^{15}N isotope carried out at the same time at a site 10 km away, where statistically significantly higher tuber yields and nitrogen utilisation from fertilisers were found in the treatment with pitting and fertilisation at loosening compared to a total N dose fertiliser application at planting (Kusá et al. 2021). The positive effect of divided doses of nitrogen on the yield of

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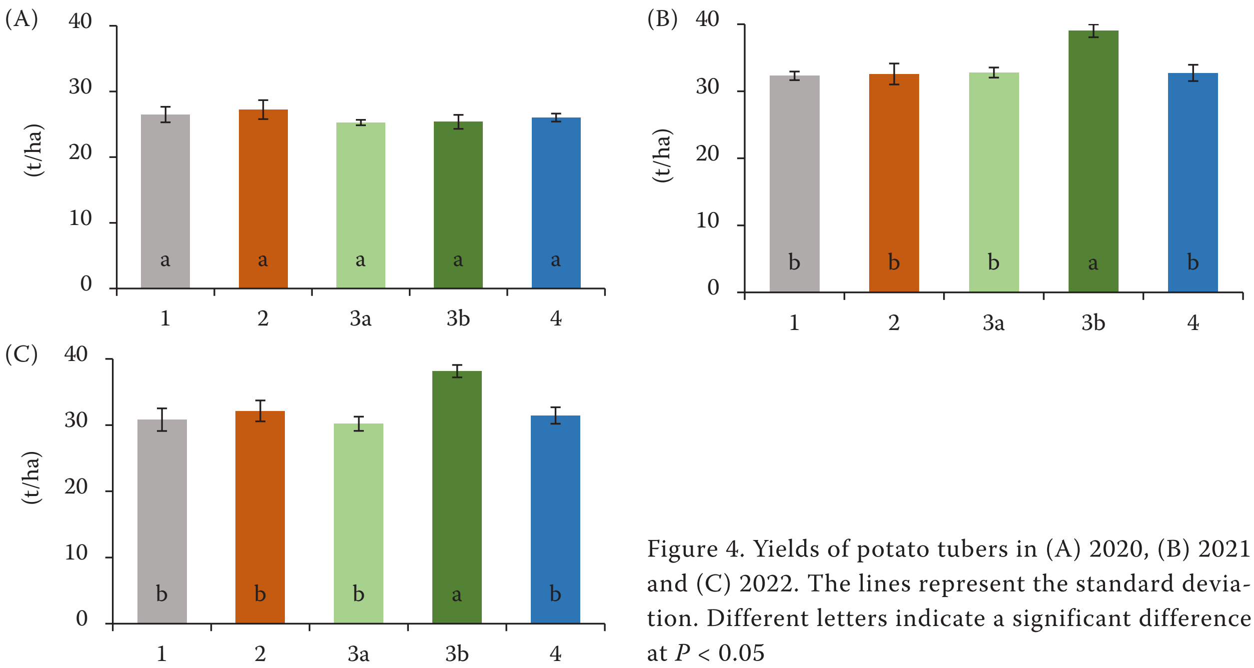

Figure 4. Yields of potato tubers in (A) 2020, (B) 2021 and (C) 2022. The lines represent the standard deviation. Different letters indicate a significant difference at $P < 0.05$

potato tubers, N utilisation and limitation of nitrate leaching, especially on sandy soils, was also confirmed by other authors (e.g. Shrestha et al. 2010, Kelling et al. 2015). The seed tuber is the primary source of nutrients and energy during sprout development, lasting approximately 30 days (Zebarth and Rosen 2007). This period is risky regarding nitrate leaching. Furthermore, high N supply at the first growth stages suppresses or delays tuber bulking (Biemond and Vos 1992).

The tested modifications of ridges and furrows reduced surface runoff and increased soil water content in the ridges compared to the control. The highest volumetric soil moisture in the ridges found in the tuber initiation phase was always the highest in the "pits" treatment and the lowest in control. The differences in individual years ranged from a few tenths of a percent to 2.2% VWC (volumetric water content). It was assumed that higher wetting of modified ridges and better water availability for plants would contribute to higher yields of potato tubers. The experiments described in this study did not unequivocally disprove the assumption, as rainfall was not a yield-limiting factor in 2020–2022.

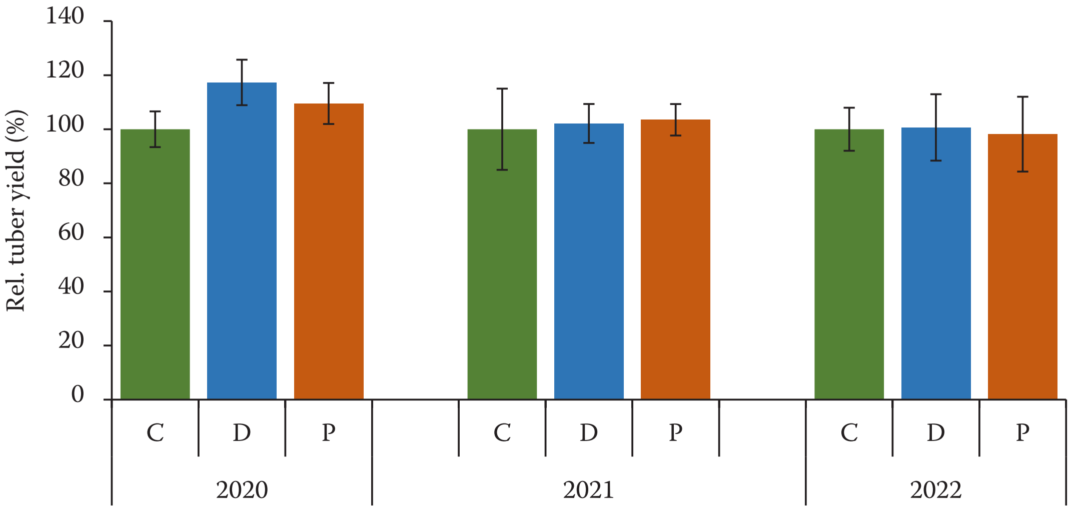

Figure 5. The relative yield of tubers on the control treatment (C) and treatment 2 under dams (D) and pits (P). Control = 100%. The lines represent the standard deviation

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Jordan et al. (2013) confirmed that more blocky ridges could significantly improve potato yield, quality, and N-use efficiency than pointed ridges on sandy soil. No modification of the top of the blocky ridges gave conclusively the best results – in two years out of three, ridges with a standard plateau were more profitable, and in the third with a shaped plateau with the groove on the top.

All ridge and furrow treatments tested were beneficial in reducing water erosion compared to the control. There was a risk of lower yields due to some treatments. The tubers planted under the pits were placed more shallowly than in the ridge with a smooth surface, and therefore the deployment of a smaller number of tubers and a lower total yield on the treatments with pits could have occurred. Tuber number per plant under the pit was always lower than under the dam (by 1–1.4 tuber/plant), but only in one year out of three, it was lower than in control smooth ridge as was found by manual harvesting of individual plants. Figure 5 documents the yields of tubers under the dam and pit at the level of 101–117% and 98–110% of the control. Shallower planting of tubers under the pits did not negatively affect the yield.

The cover crop in the trail furrow competed with potatoes for water and nutrients. Choosing a crop that does not reduce the yield of the main crop is important. Winter wheat in this study was chosen appropriately, as can be seen in Figure 4: potato tuber yields on treatment 3a, "pits + loosening + sowing," were the same or slightly higher than on treatment 4, "pit + loosening". Nyiraneza et al. (2020) also achieved favourable results with cereals. Cover crops spring barley or winter rye improved marketable tuber yields by 9–24%. On the contrary, Gitari et al. (2018) obtained significantly lower tuber yield in intercropping systems with garden peas or climbing beans. These legumes also reduced potato N uptake.

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4.5 Cukrová řepa (*Beta vulgaris* L. var. *altissima)*

Cukrová řepa patří podobně jako brambory mezi významné plodiny pěstované v mírném pásmu. Proto má v řepařských oblastech České republiky dlouhou tradici. Z hlediska hospodářského významu je důležitým zdrojem cukru a zároveň je důležitou surovinou v krmivářství a zpracovatelském průmyslu. Vedle samotné produkce sacharózy poskytuje cukrová řepa další vedlejší produkty, jako jsou řepné řízky a melasa.

Z pohledu pěstitelských nároků má cukrová řepa vysoké nároky na půdu a živiny. Nejvhodnější jsou pro ni hluboké půdy s dobrou strukturou, vyrovnaným vláhovým režimem a dostatkem organické hmoty. Cukrová řepa negativně reaguje na zhutnění půdy, neboť následně dohází k horšímu růstu kořenů, snižuje se výnos bulvy a obsah cukru. Proto je důležité při jejím pěstování dodržet správný agrotechnický postup založený na kvalitním zpracování půdy.

Technologickým způsobem pěstování je řazena mezi širokořádkové plodiny (standardní rozteč řádku je 45 cm). Při konvenčním způsobu se v podzimním období provádí hluboká orba s cílem vytvořit dostatečný prostor pro růst cukrové řepy. Kromě orby je možné využít další způsoby zpracování půdy, jako jsou hluboké kypření (podrývání) a mělké kypření. Tyto postupy mohou ovlivnit výslednou protierozní účinnost. Proto jsou v **Publikaci 8** zmíněné agrotechnické způsoby pěstování cukrové řepy porovnávány z pohledu ztráty půdy a celkového množství povrchového odtoku.

Z hlediska dalších agrotechnických způsobů pěstování cukrové řepy jsou v dnešní době k dispozici následující technologie: no-till, strip-till či pěstování v hrůbcích.

Publikace 8

Název

Vliv podzimního zpracování půdy u cukrové řepy na projevy vodní eroze.

Citace

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Vliv podzimního zpracování půdy u cukrové řepy na projevy vodní eroze

EFFECT OF AUTUMN TILLAGE IN SUGAR BEET FIELDS ON WATER EROSION

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Cukrová řepa je jednou z nejnáročnějších zemědělských plodin s přísně vyhraněnými požadavky na pěstitelská opatření (1). Základem úspěšného pěstování je úrodná půda s dostatkem živin (2). Mezi další rozhodující faktory patří důkladné zpracování půdy (3). To zpravidla začíná již na podzim, kdy je cílem připravit a urovnat povrch půdy pro jarní předseťovou přípravu (4).

V Evropě patří cukrová řepa mezi důležité zemědělské plodiny (5). Z technologického hlediska pěstování se jedná o širokořádkovou plodinu se standardní meziřádkou vzdáleností 45 cm (3). To jí umožňuje dosahovat odpovídajících výnosů, zároveň ji však řadí mezi rizikové plodiny z pohledu vodní eroze (6). Jako u většiny plodin je i v případě řepy nejrizikovější období krátce po setí, kdy není povrch půdy dostatečně chráněn před dopadajícími dešťovými kapkami (7). V případě výskytu přívalových dešťů pak může docházet k erozním událostem (8). V důsledku vodní eroze nastává celá řada problémů jak na zasaženém pozemku, tak i mimo něj (9). V místě působení vodní eroze postupně ubývá svrchní vrstva půdy (10), dochází k vyplavování živin a pozemek se stává méně úrodným (11). Pokud se smytý sediment dostane až do vodních toků, může snižovat průtočný profil (12) či způsobovat nadměrnou eutrofizaci (13), což následně zvyšuje finanční náklady na odstranění způsobených škod (14).

Za základ trvale udržitelného hospodaření jsou dnes považovány půdoochranné technologie (15). Ty jsou většinou založeny na dostatečné pokryvnosti povrchu rostlinnými zbytky či živými rostlinami. Jejich přítomnost následně snižuje rozsah degradačních procesů, mezi které patří i vodní eroze (16). Na toto téma již byla vydána řada publikací (17, 18 atd.), kde je význam půdoochranných technologií z pohledu vodní eroze i dalších aspektů podrobně popsán.

Obr. 1. Ukázka z měření simulátorem deště

Ne všechny půdoochranné technologické postupy však musí být nutně založeny na vyšší pokryvnosti půdy. Jednou z takových technologií je například podrývání, resp. hloubkové kypření půdy (19, 20). Tato agrotechnická operace umožňuje rozrušení zhutnělých podorničních vrstev, podporuje infiltraci vody do půdy (21) a je vhodné ji využívat při pěstování cukrové řepy. Hloubkové kypření je proto společně s dalšími dvěma agrotechnickými způsoby přípravy půdy předmětem tohoto článku. Jeho hlavním cílem bylo ověřit, má-li rozdílné podzimní zpracování půdy vliv na rozsah vodní eroze v jarním období krátce po setí cukrové řepy. Kromě smyvu půdy bylo dalším cílem stanovit množství povrchového odtoku.

Materiál a metody

Hodnocení podzimního zpracování půdy u cukrové řepy z hlediska omezení vodní eroze bylo prováděno v okrese Jičín, který jako územně-správní jednotka spadá do Královéhradeckého kraje. Ověřování bylo prováděno pomocí polního simulátoru deště (obr. 1.) vyvinutého ve Výzkumném ústavu monitoringu a ochrany půdy (VÚMOP). Pro účel tohoto hodnocení byly zakládány jednotlivé experimentální pozemky s požadovaným způsobem zpracování půdy. Pokusy byly prováděny po dobu čtyř let, přičemž pokusné plochy byly orientovány po spádnici, což je nejméně příznivý způsob z hlediska omezení vodní eroze. Konkrétně byly prověřovány tyto varianty:

– **hluboká orba** s hloubkou zpracování 25 cm,
– **hluboké kypření** s hloubkou zpracování 25 cm,
– **mělké kypření** s hloubkou zpracování 13 cm.

Podzimnímu zpracování půdy předcházela aplikace chlévského hnoje v dávce 50 $t \cdot ha^{-1}$ s následnou podmítkou talířovým podmítačem. V jarním období rovněž u všech variant proběhla předseťová příprava realizovaná kompaktorem s hloubkou zpracování 3 cm. Do této hloubky se následně i zaselo přesným secím strojem.

Klimatické a půdní poměry

Měření byla provedena v klimatickém regionu T3, který je charakterizován průměrnou teplotou 8–9 °C, sumou teplot nad 10 °C v rozmezí 2 500–2 800 °C, průměrným úhrnem srážek 550–650 mm a pravděpodobností suchých vegetačních období mezi 10–20 %. Přestože se pokusné plochy v jednotlivých letech měnily, sklonitost dosahovala minimálně 6 %. Zároveň bylo dbáno, aby se na pokusných plochách nacházel stejný půdní typ – hnědozemě s relativně podobnými půdními parametry. Jako indikátor charakteru půdních podmínek uvádíme jeden z půdních rozborů. Zrnitostní složení odpovídalo půdnímu druhu – hlinitá půda. Podíl jednotlivých frakcí byl < 0,002 mm – 23,6 %, < 0,01 mm – 35,7 %, < 0,05 mm – 84,9 %, < 0,1 mm – 94,2 %. Obsah humusu byl 1,98 %, tedy půda byla slabě humózní, což odpovídá obsahu oxidovatelného uhlíku (C_{ox}) 1,15 %. Výměnná půdní reakce pH_{KCl} dosáhla hodnoty 5,7. Půdní reakce byla tedy mírně kyselá. Rychlost infiltrace po nasycení odpovídala rozmezí 0,1–0,2 $mm \cdot min^{-1}$. To znamená, že půda je schopna středně rychle vsakovat vodu i při plném nasycení půdního prostředí.

Postup měření polním simulátorem deště

Princip měření pomocí polního simulátoru deště spočívá v rozstřiku vody na přesně definovanou ohraničenou plochu 21 m^2, kdy se zaznamenává průběh a množství povrchového odtoku. Zároveň se v pravidelných intervalech (3 min) odebírají vzorky odtékající vody, ze kterých se následně laboratorně stanovuje obsah nerozpuštěných látek. Tyto hodnoty se po zpracování doplňují do softwaru simulátoru, který ze zaznamenaného průběhu odtoku vypočte celkovou ztrátu půdy vodní erozí pro řešenou variantu. Schéma ověřování bylo pro každou variantu (pokusnou parcelu) totožné, přičemž první zadeštění probíhalo po dobu 20 minut. Následovala technologická pauza z důvodu sjednocení vlhkostních poměrů a načerpání nové vody. A poté se provedla druhá simulace na již vlhkou půdu, jejíž délka byla stejná jako u prvního zadeštění, tedy rovněž trvala 20 minut. Jednotlivé termíny měření vycházejí z pěstebních období stanovených pro určení faktoru ochranného vlivu vegetačního pokryvu (22):

– první termín zadeštění – v období od přípravy pozemku k setí do jednoho měsíce po zasetí,
– druhý termín zadeštění – v období od druhého měsíce po jarním nebo letním setí,
– třetí termín zadeštění – v období od konce druhého termínu zadeštění do sklizně.

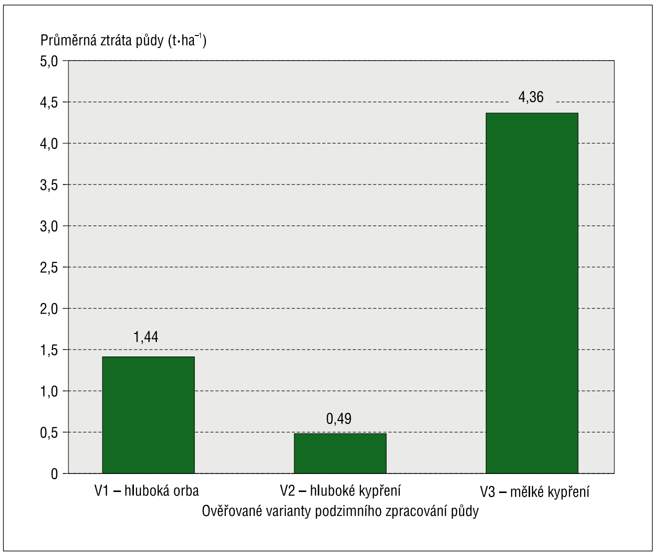
Výsledky

Podzimní příprava půdy pro cukrovou řepu má klíčový význam v prevenci vodní eroze. Jedním z důležitých faktorů je hloubka zpracování půdy, při níž pracovní orgány stroje narušují utuženou vrstvu. Tato vrstva se na půdách vhodných pro pěstování cukrové řepy obvykle nachází v hloubce od 22 cm. I při hlubším zpracování však existují významné rozdíly mezi jednotlivými technologiemi, které ukazují na vyšší účinnost některých postupů. Hloubka zpracování tedy není jediným faktorem, který ovlivňuje míru vodní eroze. Značný vliv má i způsob, pomocí kterého je půda v podzimním období připravena (orba, hluboké nebo mělké kypření). Tuto skutečnost nejlépe potvrzují výsledky měření simulátorem deště, které stanovují průměrnou ztrátu půdy a průměrnou výšku povrchového odtoku.

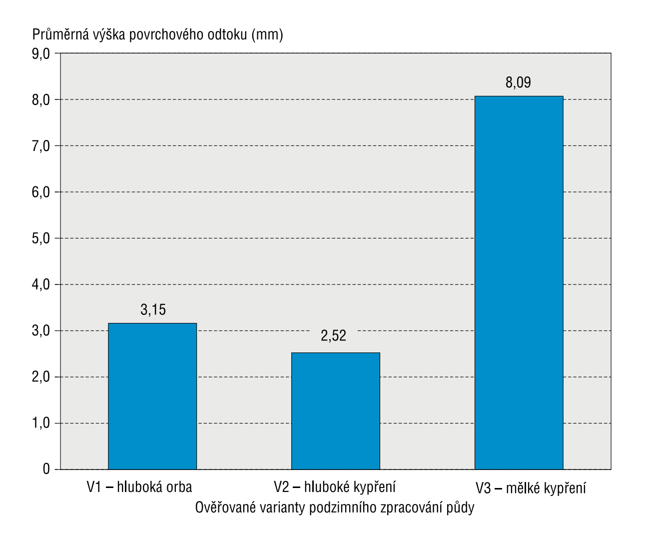
Ztráta půdy

Výsledky ztráty půdy hodnotí míru odlučnosti půdních částic vlivem vodní eroze. Samozřejmě do určité míry je výsledná ztráta půdy v korelaci s množstvím povrchového odtoku, ale rovněž se do výsledku promítají i další faktory. Proto si nejprve představme samotné výsledky ztráty půdy (obr. 2.) a následně přepočtené na jednotku povrchového odtoku. Nejvyšší ztráta půdy byla zaznamenána u varianty mělkého kypření, kde dosáhla hodnoty 4,36 $t \cdot ha^{-1}$. Tento výsledek přisuzujeme především hloubce zpracování, která byla významně nižší než u zbývajících ověřovaných variant. U hluboké orby dosáhla průměrná ztráta půdy 1,44 $t \cdot ha^{-1}$. Efekt hlubšího zpracování půdy oproti předchozí variantě je zde tedy poměrně zřetelný. Nejnižší ztrátu půdy, pouze 0,49 $t \cdot ha^{-1}$, prokázala varianta hlubokého kypření. Tento výsledek je pravděpodobně dán kvalitnějším zpracováním

Obr. 2. Průměrná ztráta půdy vodní erozí stanovená na podkladě měření simulátorem deště



Obr. 3. Průměrná výška povrchového odtoku u ověřovaných variant podzimního zpracování půdy



a rozrušením utužené vrstvy půdy. Do výsledku se však pozitivně promítají i další faktory jako drsnost povrchu půdy jednotlivých variant, struktura či stabilita půdních agregátů. To je zřetelné, přepočteme-li si výsledky ztráty půdy na jednotku odtoku. U mělkého kypření odpovídá ztráta půdy hodnotě 0,54 $t{\cdot}ha^{-1}{\cdot}mm^{-1}$, u hluboké orby 0,46 $t{\cdot}ha^{-1}{\cdot}mm^{-1}$ a u hlubokého kypření pouze 0,19 $t{\cdot}ha^{-1}{\cdot}mm^{-1}$. Zatímco se tedy u hluboké orby a mělkého kypření se na jednotku odtoku ztrácely půdní částice podobně, u hlubokého kypření je hodnota méně než poloviční.

Průkaznost výsledků průměrné ztráty půdy byla prověřována pomocí testu One Way ANOVA. Mezi variantami byl na hladině významnosti $\alpha = 0{,}05$ prokázán rozdíl. Následně byly výsledky prověřovány i Tukey HSD testem, který ověřoval rozdíly mezi jednotlivými variantami. S vysokou pravděpodobností 0,009 byl potvrzen rozdíl mezi variantou hlubokého a mělkého kypření. Pouze o necelá dvě procenta se nepodařilo prokázat rozdíl mezi variantami hluboká orba a mělké kypření, kde výsledné p-value dosáhlo hodnoty 0,057. U výsledků variant hluboké orby a hlubokého kypření p-value dosáhlo hodnoty 0,732. Výsledky obou testů jsou uvedeny v tab. I.

Výška povrchového odtoku

Průměrná výška povrchového odtoku stanovuje množství vody, která povrchově odtekla za daný časový interval, tj. dobu simulace 40 minut. Výška povrchového odtoku je vyjádřená svislou výškou vodního sloupce rovnoměrně rozloženého na ploše, která se vztahuje k rozměru zadešťované plochy 21 m^2. Výsledky průměrné výšky povrchového odtoku (obr. 3.) ukazují, jak různé způsoby zpracování půdy ovlivňují množství povrchového odtoku, ale ekvivalentně i to, jak jsou schopny zadržet srážkovou vodu. Shodně jako v případě kritéria ztráty půdy byla nejvyšší hodnota odtoku zjištěna u mělkého kypření, a to 8,09 mm. Tato hodnota byla 2,5–3,2× vyšší než u zbylých dvou způsobů podzimního zpracování půdy. Mělké kypření má výrazný vliv na menší infiltraci vody do půdy, což vede k většímu množství povrchového odtoku. Naopak, hluboká orba s průměrnou hodnotou odtoku 3,15 mm vykazuje lepší schopnost zadržet vodu. Nejnižší hodnotu odtoku vykázala varianta hluboké kypření s hodnotou 2,52 mm, což naznačuje, že tento způsob zpracování nejvíce podporuje infiltraci vody a snižuje povrchový odtok.

Průkaznost výsledků průměrné výšky povrchového odtoku byla opět prověřována dvojicí statistických testů – One Way ANOVA s následnou aplikací Tukeyho HSD testu. One Way ANOVA test na hladině významnosti $\alpha = 0{,}05$ prokázal mezi všemi variantami statisticky významný rozdíl. Následný Tukeyho test potvrdil významný rozdíl mezi variantami mělkého kypření a hluboké orby, přičemž p-value zde dosáhlo hodnoty 0,004. S velkou spolehlivostí byl potvrzen statisticky významný rozdíl i mezi mělkým a hlubokým kypřením, kde p-value bylo pouze 0,001. Naopak mezi hlubokou orbou a hlubokým kypřením statistický průkazný rozdíl prokázán nebyl, protože p-value dosáhlo hodnoty 0,904. Výsledky testů potvrzují, že rozdíly mezi variantami mělkého a hlubokého kypření a mezi mělkým kypřením a hlubokou orbou jsou statisticky významné, zatímco rozdíl mezi hlubokou orbou a hlubokým kypřením není potvrzen. Výsledky obou testů jsou uvedeny v tab. II.

Diskuse

Pěstování cukrové řepy představuje výzvu nejen z hlediska dosažení vysokých výnosů a snižování nákladů díky použití vhodných agrotechnických postupů, ale rovněž z pohledu udržitelného hospodaření s půdou a vodou. Tento požadavek zahrnuje ochranu proti vodní erozi i efektivní zadržování vody v půdním profilu.

Vzhledem k těmto požadavkům se v posledních letech stále častěji zkoumají různé technologické postupy, jejichž cílem je zajistit dlouhodobě udržitelné způsoby hospodaření. Klíčovou roli v tomto směru hrají postupy zpracování půdy mající výrazný vliv na míru povrchového odtoku a ztrátu půdy vodní erozí. Jak dokládá tato studie, při celoplošném zpracování půdy je významným faktorem právě hloubka zpracování půdního profilu.

Poměrně odlišné výsledky ovšem publikovali Johnson a Moldenhauer (23). Jejich experiment porovnával vliv podzimního zpracování pluhem do hloubky 20 cm, podzimního mělkého zpracování dlátovým kypřičem do hloubky 15 cm (varianta podobná našemu mělkému kypření) a variantu jarního povrchového kypření disky. Stejně jako v naší studii byly výsledky odtoku a ztráty půdy stanoveny na základě simulovaných srážek. První simulace srážky trvala 60 min, po 24 h byla aplikována druhá simulace srážky

Tab. I. Výsledky statistických testů u kritéria ztráta půdy

Varianta	Počet měření	Průměrná ztráta půdy ($t{\cdot}ha^{-1}$)	ANOVA (p-value)	Tukey HSD test (p-value)
V1 – hluboká orba	18	1,44		V1 vs. V2 = 0,732
V2 – hluboké kypření	17	0,49	0,009	V1 vs. V3 = 0,057
V3 – mělké kypření	18	4,36		V2 vs. V3 = 0,009

po dobu 30 min a po 15min přestávce byla spuštěna i třetí simulace s délkou 30 min. Intenzita simulované srážky byla 6,35 cm za hodinu.

– Při první simulaci byla nejvyšší ztráta půdy zaznamenána u varianty orby pluhem, a to 11,70 t·ha^{-1}·h^{-1}. Výrazně nižší ztráta byla zjištěna u mělkého zpracování dlátovým kypřičem (2,67 t·ha^{-1}·h^{-1}, což představuje snížení o 77 %) a podobně i u povrchového kypření disky (2,69 t·ha^{-1}·h^{-1}).
– Při druhé simulaci na nasycené půdě byla opět nejvyšší ztráta půdy zaznamenána u orby pluhem (21,94 t·ha^{-1}·h^{-1}). Ztráta u varianty povrchového kypření disky však výrazně vzrostla na 17,85 t·ha^{-1}·h^{-1} (snížení pouze o 19 %). Podzimní mělké zpracování dlátovým kypřičem mělo nejnižší hodnotu ztráty půdy 5,57 t·ha^{-1}·h^{-1} (snížení o 75 %).
– Ve třetím termínu simulace byly předchozí výsledky pouze potvrzeny. U orby pluhem dosáhla ztráta 22,94 t·ha^{-1}·h^{-1}. U povrchového kypření disky byla ztráta půdy 18,82 t·ha^{-1}·h^{-1} (snížení o 18 %) a u varianty mělkého dlátového kypření 7,48 t·ha^{-1}·h^{-1} (snížení o 67 %).

Tab. II. Výsledky statistických testů u kritéria výška povrchového odtoku

Varianta	Počet měření	Průměrný povrchový odtok (mm)	ANOVA (p-value)	Tukey HSD test (p-value)
V1 – hluboká orba	18	3,15		V1 vs. V2 = 0,904
V2 – hluboké kypření	17	2,52	0,001	V1 vs. V3 = 0,004
V3 – mělké kypření	18	8,09		V2 vs. V3 = 0,001

Poměrně velké rozdíly mezi výsledky této studie a námi zjištěnými jsou překvapivé, protože půdní a sklonové podmínky pokusu byly podobné (zrnitost půdy prachovitá hlína, sklon pozemku 5 %). Určitý rozdíl je možno zaznamenat v hloubce zpracování, u orby (o 5 cm) a u mělkého kypření (o 2 cm), ale nedomníváme se, že by měl mít tak výrazný vliv. Dalším rozdílem je, že výsledky v naší studii byly měřeny průběžně během celé vegetační doby cukrové řepy, zatímco studie Johnsona a Moldenhauera (23) prováděla měření v krátkém období během konce května a začátku června na půdě bez vegetace. A právě tato skutečnost by mohla být hlavní příčinou rozdílných výsledků. Hnědozemě, na kterých jsme ověřovali, měly během vegetační sezony schopnost se vlivem klimatických poměrů samy přirozeně utužovat. Rozdílný způsob podzimního zpracování pak mohl mít zásadní vliv na strukturu orniční vrstvy. Efekt genetického (přirozeného) utužování popisuje i metodika Javůrek a Vach (24) a je obvyklá u těžších typů půd.

Naopak podobné závěry o vlivu hloubky zpracování při pěstování cukrové řepy přinesla studie Jabro et al. (25). Ta zkoumala mělké zpracování pomocí diskového kypřiče a středně hluboké zpracování dlátovým kypřičem, přičemž vycházela z rozdílu v nasycené hydraulické vodivosti. Hloubka zpracování však opět nebyla zcela totožná – u diskového kypřiče byla hloubka o 3 cm menší a u dlátového kypřiče o 5 cm nižší. Přesto průměrná hodnota nasycené vodivosti u středně hlubokého zpracování dosáhla 41,5 mm·h^{-1}, zatímco u mělkého zpracování to bylo 30,4 mm·h^{-1}. Varianta hlubšího zpracování tak infiltrovala o 37 % více vody. Autoři tento výsledek přisuzují zejména nižšímu utužení půdy. Dalšími efekty hlubšího zpracování byly mírně vyšší vlhkost půdy a zvýšená pórovitost.

Další porovnání výsledků s jinými studiemi již není přímé, protože kromě hloubky zpracování a použité agrotechniky se do výsledků promítají i rostlinné zbytky. Obecně jejich příznivý vliv na omezení vodní eroze popisují McCarthy et al. (26), da Silva et al. (27) a Janeček (28). V souvislosti s pěstováním cukrové řepy takovou studii uvádí i Scholtz et al. (6). Práce hodnotila čtyři způsoby zpracování půdy, konkrétně konvenční zpracování půdy s opakovaným použitím pluhu, redukované zpracování s jednorázovým použitím pluhu a výsevem meziplodiny, půdoochranné zpracování založené na podrývání a výsevu meziplodiny a poslední variantou byl no-till, rovněž s podrýváním a výsevem meziplodiny. U všech variant kromě no-tillové byla provedena předseťová příprava rotačními branami v jarním období. Nejvyšší hodnoty ztráty půdy byly zaznamenány u konvenční varianty. Redukované zpracování mělo ztrátu nižší o 69 % a půdoochranné o 93 %. Nejlepší výsledek však byl zaznamenán u varianty no-till, kde byla ztráta půdy snížena o 98 %. Dosažené hodnoty jsou ještě významnější než u námi hodnocených variant. Tedy kombinace hlubšího zpracování půdy s dostatečným množstvím rostlinných zbytků se jeví z hlediska omezení eroze jako nejpříznivější. Rostlinné zbytky působí jako drobné překážky odtoku vody po povrchu, omezují přímý kontakt s půdou a zvyšují infiltraci srážkové vody. Zároveň v dlouhodobém měřítku tato kombinace také zlepšuje strukturu půdy, která má příznivý dopad na celou řadu fyzikálních a chemických vlastností půdy.

Určitý kompromis mezi konvenčním zpracováním půdy a postupy s velkým množstvím rostlinných zbytků na povrchu nabízí technologie pásového zpracování půdy (strip-till). Ta se obvykle využívá při protierozním pěstování kukuřice (29), slunečnice (30) nebo řepky (31). Nicméně, jak popisuje práce Laufer et al. (32), i tímto postupem lze úspěšně pěstovat cukrovou řepu s minimálními dopady na půdu. Hodnoceny byly tři způsoby zpracování půdy: intenzivní orba s hloubkou 20 – 30 cm, redukované zpracování kultivátorem do hloubky 17 – 22 cm a pásové zpracování půdy (strip-till) rovněž s hloubkou zpracovaných pásů 17 – 22 cm. Redukované zpracování bylo provedeno do porostu ozimé meziplodiny hořčice bílé a pásové zpracování do rostlinných zbytků obiloviny, která se zde nacházela v roce předchozím. I v tomto pokusu byly nejhorší výsledky zjištěny u varianty orby. V případě povrchového odtoku tato varianta dosáhla průměrné hodnoty 7,8 l·m^{-2}, a u kritéria ztráty půdy dosáhla 468 g·m^{-2}. Nepoměrně lepší výsledky byly zjištěny u varianty redukovaného zpracování s rostlinnými zbytky na povrchu, kde povrchový odtok dosáhl hodnoty 3,5 l·m^{-2} (snížení o 55 %) a ztráta půdy 70 g·m^{-2} (snížení o 85 %). Ještě lepší hodnoty byly zjištěny u pásového zpracování půdy, kde povrchový odtok činil pouze 0,6 l·m^{-2} (snížení o 92 %) a ztráta půdy 9 g·m^{-2} (snížení o 98 %). Tato práce tedy opět potvrzuje pozitivní vliv kombinace hlubšího zpracování půdy s rostlinnými zbytky na povrchu.

Výsledky odtoku a ztráty půdy jsou silně ovlivněny celou řadou faktorů, které mohou mít různý vliv v závislosti na konkrétních podmínkách. Kromě hloubky zpracování půdy a použitých agrotechnických metod hrají významnou roli také klimatické podmínky, intenzita a distribuce srážek, stav půdní struktury a vegetační pokrytí. Například v suchých obdobích může mít i mírné zpracování půdy výrazně odlišné výsledky než v obdobích s vysokými srážkami, kdy je půda více nasycená vodou. Je tedy zřejmé, že každá změna v jedné z těchto proměnných může vést k odlišným výsledkům, což činí vyhodnocování účinnosti agrotechnických opatření složitým. Přesto u většiny studií můžeme pozorovat pozitivní trend vlivu hloubky zpracování ve vztahu k projevům vodní eroze.

Závěr

Pěstování cukrové řepy je zemědělskou činností, která vyžaduje precizní péči o půdní podmínky, zejména vzhledem k riziku vodní eroze, která může vést k ztrátám úrodné půdy a znečištění vodních toků. Tato studie se zaměřila na vliv různých technologií podzimního zpracování půdy na míru vodní eroze ve vegetačním období růstu cukrové řepy.

Nejnižší ztrátu půdy vykazovala varianta hlubokého kypření, která zajišťuje nejlepší podmínky pro infiltraci vody do půdy, čímž se snižuje povrchový odtok. Naopak, mělké kypření mělo největší vliv na zvýšení povrchového odtoku a ztrátu půdy. I u hluboké orby se stejnou hloubkou zpracování jako u hlubokého kypření byly projevy vodní eroze horší. Tento výsledek potvrzuje, že kromě hloubky zpracování hraje roli i struktura půdy a její schopnost absorbovat vodu, což vede k lepší ochraně před vodní erozí.

Výsledky této studie potvrzují, že správně zvolené technologické postupy mohou významně přispět k udržitelnému hospodaření, zlepšení zadržování vody v půdě a ochraně proti vodní erozi. Důraz na hluboké kypření a podobné půdoochranné technologie může vést k minimalizaci negativních dopadů eroze, což je klíčové pro dlouhodobou produktivitu půdy a ochranu životního prostředí.

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Souhrn

Příspěvek je zaměřen na ověření vlivu podzimního zpracování půdy z hlediska omezení vodní eroze v porostech cukrové řepy. Celkově byly z hlediska vlivu na ztrátu půdy a množství povrchového odtoku hodnoceny 3 varianty: hluboká orba, mělké a hluboké kypření. Tato dvě kritéria byla po dobu 4 let měřena polním simulátorem deště, který se již standardně v České republice používá pro stanovení protierozního účinku plodin a jednotlivých půdoochranných technologií. Jednoznačně nejhorší výsledky byly zaznamenány u mělkého kypření. Tato varianta vykázala vysokou hodnotu ztráty půdy 4,36 $t \cdot ha^{-1}$ a výšku povrchového odtoku 8,09 mm. Nepoměrně lepší výsledky byly zjištěny u hluboké orby, kde průměrná ztráta půdy dosáhla 1,44 $t \cdot ha^{-1}$ a povrchový odtok 3,15 mm. Použitý statistický test ovšem potvrdil průkaznost rozdílu mezi mělkým kypřením a hlubokou orbou pouze v případě výšky odtoku (ztráta půdy p-value 0,057, výška povrchového odtoku p-value 0,004). Nejlepší výsledky byly zaznamenány u hlubokého kypření, kde ztráta půdy dosáhla pouze 0,49 $t \cdot ha^{-1}$ a výška povrchového odtoku 2,52 mm. Statistické zpracování dat jednoznačně prokázalo rozdíl mezi mělkým a hlubokým kypřením u obou sledovaných kritérií (ztráta půdy p-value 0,009, výška povrchového odtoku p-value 0,001). Mezi variantami hlubokého kypření a orby se rozdíl nepodařilo zjistit (ztráta půdy p-value 0,732, výška povrchového odtoku p-value 0,904). Z výsledků plyne, že hloubka zpracování má vliv na projevy eroze. Přestože statistický test neprokázal průkazný vliv hlubokého kypření oproti hluboké orbě, dosažené průměrné hodnoty odtoku a ztráty půdy naznačují, že tato varianta by při stejné hloubce zpracování mohla být optimálnější z hlediska omezení vodní eroze.

Klíčová slova: vodní eroze, zpracování půdy, cukrová řepa, povrchový odtok, ztráta půdy.

Obr. 4. Podzimní hluboké kypření může přispět k lepšímu zadržování vody v půdě a ochraně proti vodní erozi

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Kincl D., Kabelka D., Vopravil J.: Effect of Autumn Tillage in Sugar Beet Fields on Water Erosion

TThis paper aims at verifying the effect of autumn tillage in terms of reducing water erosion in sugar beet crops. The following 3 options were evaluated in terms of their effect on soil loss and the amount of surface runoff; they were deep ploughing, shallow loosening and deep loosening. The two criteria above were measured over the period of 4 years using a field rain simulator, which has been commonly used in the Czech Republic to determine the anti-erosion effect of crops and individual soil conservation technologies. The worst results were recorded for shallow loosening. This method showed a high soil loss value of 4.36 t·ha^{-1} and a surface runoff height of 8.09 mm. Comparatively better results were recorded in deep ploughing, with the average soil loss 1.44 t·ha^{-1} and surface runoff 3.15 mm. However, the statistical test used confirmed the significance of the difference between shallow loosening and deep ploughing only in the case of runoff height (soil loss p-value 0.057, surface runoff p-value 0.004). The best results were recorded for deep loosening, where the soil loss was only 0.49 t·ha^{-1} and the height of surface runoff was 2.52 mm. Statistical processing of the data clearly showed a difference between shallow and deep loosening for both criteria studied (soil loss p-value 0.009, height of surface runoff p-value 0.001). No difference was found between deep loosening and deep ploughing (soil loss p-value 0.732, height of surface runoff p-value 0.904). The results show that the depth of cultivation has an effect on erosion symptoms. Although the statistical test did not show a conclusive effect of deep loosening compared to deep ploughing, the average values obtained for runoff and soil loss suggest that this method could be more optimal in terms of reducing water erosion at the same depth of cultivation.

Key words: water erosion, tillage, sugar beet, surface runoff, soil loss.

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4.6 Povrchový odtok jako součást vodní eroze

Jak již bylo zmíněno v úvodní části, vodní eroze je jedním z nejčastějších degradačních procesů vyskytujících se na zemědělské půdě. Vzniká na sklonitých pozemcích působením přívalových srážek. Ty uvolňují a přenášejí půdní částice do nižších částí na různě velké vzdálenosti. Při tomto procesu hraje klíčovou roli povrchový odtok, respektive jeho množství a kinetická energie určující schopnost unášet a odlučovat půdní částice. Informace o množství povrchového odtoku u jednotlivých způsobů hospodaření jsou uvedeny v předchozích publikacích (**Publikace 1**, **3**, **4**, **5**, **6**, **7**, **8**).

Ke vzniku povrchového odtoku dochází v momentě, kdy intenzita srážek překročí infiltrační kapacitu půdy. Infiltrační kapacita půdy je ovlivněna řadou faktorů: půdní druh, množství organické hmoty, drsnost povrchu, aktuální vlhkost apod. Tímto tématem se zabývá **Publikace 9**. Jejím obsahem je hodnocení vlivu jednotlivých zrnitostních frakcí půdy a aktuální vlhkosti na rychlost infiltrace.

Povrchový odtok je přirozenou součástí hydrologického cyklu, nicméně celkové množství odtékající vody ze zemědělské půdy je možné poměrně výrazně ovlivnit způsobem hospodaření. V zásadě lze tvrdit, že povrchový odtok je hlavním faktorem, který mám vliv na rozsah vodní eroze. Pokud dojde k omezení množství povrchového odtoku, je omezeno množství smytých částic. Mezi povrchovým odtokem a vodní erozí však není přímá úměra, což potvrzuje **Publikace 9**. Výsledný rozsah vodní eroze je dán celou řadou dalších faktorů (půdní druh, množství organické hmoty v půdě, pokryvnost povrchu rostlinnými zbytky, stabilita půdních agregátů apod.). Rovněž je potřeba dodat, že kromě povrchového odtoku způsobuje vodní erozi půdy také samotný dopad dešťových kapek (tzv. kapková eroze) nebo eroze působená hypodermickým (podpovrchovým) odtokem.

Při využívání konvenčních technologií na svažitých pozemcích (kde to legislativa dovolí) mohou mít důsledky vodní eroze negativní dopady na životní prostředí (viz kapitola 2.1). **Publikace 10** se proto zabývá možnostmi, pomocí kterých by bylo možné zachytávat smytý sediment přímo na pozemku. Jedná se o různá mobilní technická protierozní opatření, jejichž problematika není doposud v České republice příliš prozkoumána.

Celkové množství povrchového odtoku je možné předpovídat na základě celé řady modelů. Jedním z celosvětově nejpoužívanějších modelů je metoda CN křivek.

Publikace 11 je cíleně zaměřena právě na problematiku předpovědi povrchového odtoku pomocí CN křivek u vybraných plodin a jejich agrotechnických postupů.

Publikace 9

Název

Measuring of infiltration rate in different types of soil in the Czech Republic using a rainfall simulator.

Citace

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Measuring of infiltration rate in different types of soil in the Czech Republic using a rainfall simulator

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Abstract: Knowledge of the issue of water movement in the soil is the basis for agricultural activity, but also for many other sectors. One of the basic indicators that is evaluated in soil science is the rate of water infiltration into the soil. The article specifically states how soil texture and soil moisture affect the rate of water infiltration. The results show that changes in water infiltration can be significant and certain trends can be traced. The rate of water infiltration into the soil is most affected by the sand fraction (soil particles 0.05–2 mm). The higher the percentage of these soil particles in the soil, the lower the changes in infiltration rate depending on the degree of saturation. The article further evaluates soil moisture in relation to texture. The results were obtained at several research locations within the period 2014–2021 in the territory of the Czech Republic. The above findings are primarily applicable to the region of Central Europe or can be used as comparative values for regions in the rest of the world.

Keywords: soil erodibility; soil moisture; soil texture; surface runoff; water infiltration rate

The water infiltration rate into soils is one of the critical factors that influence the soil water regime (Novák & Hlaváčiková 2019). It indicates how much precipitation will be in the form of surface runoff and how much will infiltrate into the soil (Rawls et al. 1992). The higher the infiltration capacity of the topsoil, the more water can infiltrate (Suttisong & Rattanadecho 2011). Knowledge of soil water flow and its variations is needed in many environmental fields, such as runoff modelling (Chandler et al. 2018), soil conservation (Heard et al. 1988), irrigation systems (Bhardwaj et al. 2007), slope stability (Vardon et al. 2016), land drainage (Youngs 1976), earth dam design (Ferdos et al. 2015) or flood management (Simpson & Meixner 2012).

The process of water infiltration is reported to be affected by many factors such as soil properties, underlying surface or rainfall characteristics (Ahuja et al. 2007; Neris et al. 2012). Most soil physical properties are highly variable throughout the year,

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but soil texture is relatively stable. Therefore, this article is primarily focused on verifying the relationship between water infiltration and soil texture. The problematics of water infiltration and surface runoff is also important in relation to climate change. The probability of extreme weather occurrence (torrential rains or droughts) has increased in the last decades (Kornhuber et al. 2019) and this trend is still continuous (Min et al. 2011; Zwiers et al. 2011). Extreme climatic conditions fundamentally affect a number of important soil properties (Seneviratne et al. 2010). One of these properties is soil moisture, which is closely related to infiltration rate. For this reason, this property of the soil is also evaluated in the article. Of course, there are other factors that affect the infiltration rate, such as the amount of organic matter in the soil (Nemes et al. 2005), soil structure (Kodešová et al. 2009), soil compaction (Zhang et al. 2006) etc., but these are not the focus of this paper.

The main goal of the article is to verify how much initial moisture in soils with different textures affects water infiltration. Three hypotheses are verified in this article:

The relationship between water infiltration rate and soil texture could be determined.

There is a relationship between initial soil moisture and water infiltration rate.

Relationship between water infiltration rate and soil loss.

MATERIAL AND METHODS

The research was carried out between 2014 and 2021. A rainfall simulator was used to measure water infiltration in the soil. It is a research device used worldwide to study soil erosion and hydrological processes (Dunkerley 2008; Rodrigo-Comino et al. 2018). The rainfall simulator provides a comprehensive set of information from which infiltration rate can be determined. The principle of measuring using a rainfall simulator is based on the simulation of precipitation in a defined area. The rainfall simulator developed at Research Institute for Soil and Water Conservation (RISWC) was used for the research, where the size of defined area for simulation is 21 m^2 (Kabelka et al. 2019; Hofbauer et al. 2023). The device has four nozzles (fulljet type) at a height of 3.0 m, which are connected by a pipe system. Each nozzle covers an area up to an angle of 104° at a pressure of 34.5 kPa. The size of the water drops is close to the size of natural raindrops (Kovář et al. 2012). The intensity of the simulated rainfall was set around 1 mm/min.

During each term of measuring, two rainfall simulations were performed on the same area. The main aim was to verify soil with initial moisture and subsequently the soil with higher moisture obtained from the first rainfall simulation. Before each simulation, soil samples were taken from the experimental plot to determine soil moisture by the gravimetric method as soil water content by mass in % according to the formula:

$$\text{\% Soil water} = \frac{\text{Weight of wet soil}(g) - \text{Weight of dry soil}(g)}{\text{Weight of dry soil}(g)} \times 100$$

Disturbed soil samples for moisture determination were always taken in the upper part of the simulated area in the space below the fourth nozzle. The upper layer of soil with a size of 50 cm^3 was taken. The total time of the first rainfall simulation was 30 min. Then there was a technological 15-min break. During the technological break, another disturbed sample was taken at the moment when all the water had already infiltrated and the surface runoff from the first simulation had ended. A 15-min break was followed by a second rainfall simulation with duration of 15 min. During rainfall simulations, the amount of infiltrated water and surface runoff were measured. The surface runoff was collected in a water-collecting flume in the lower part of the experimental area. Its amount was determined using a tipping bucket. From these measured data, the average infiltration rate of the soil in mm/min was calculated as a difference between surface runoff and the water that infiltrated the soil.

Infiltration rate was always monitored on the bare soil. Bare soil means an experimental plot completely without plant cover prepared according to the methodology Wischmeier and Smith (1965) and Guideline "Erosion Control in the Czech Republic – Handbook" by Janeček et al. (2012). This methodology was the same on all experimental plots. The research was carried out at eight locations in the Czech Republic (Figure 1). During the research, 8 to 20 measurements were made at individual locations, always on the same plot (Table 2). The altitude of the sites varied between 300 and 545 m and the slope 5–10°. A more detailed description, including coordinates, is given below:

(1) Třebsín (49.8542853N, 14.4639703E) – the study area si located in Central Bohemia. The summer climate is slightly warm and humid. The mean

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annual rainfall is 550–650 mm and has a temperature of 7–8 °C.

(2) Solopysky (50.2590500N; 13.7421208E) – the study area is located in Ústí Region. The typical summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and the average temperature 7–8.5 °C.

(3) Jevíčko (49.6561078N; 16.7089289E) – the study area is located in Moravia. The summer climate is warm, dry to slightly dry with an average annual temperature of 8.4 °C. Annual precipitation ranges from 650 to 750 mm.

(4) Věž (49.5645353N; 15.4508692E) – the study area is located in Vysočina (area of the Bohemian-Moravian Highlands). The summer climate is mild to slightly cold with an average annual temperature of 7.2 °C and annual precipitation of 600–750 mm.

(5) Petrovice (49.5523536N, 14.3295014E) – the study area is located in Central Bohemia, the summer climate is slightly dry and humid. The mean annual precipitation is 550–650 mm and the temperature is 7–8 °C.

(6) Skoupý (49.5763589N, 14.3567811E) – the study area is located in Central Bohemia, the summer climate is slightly dry and humid. The mean annual rainfall is 550–650 mm and the temperature is 7–8 °C.

(7) Valečov (49.6388550N, 15.4891042E) – the study area is located in Vysočina, especially in the area of the Bohemian-Moravian Highlands. The summer climate is slightly dry and humid. The mean annual rainfall is 650–750 mm and the temperature is 6–7 °C.

(8) Puclice (49.5864069N, 13.0128503E) – the study area is located in Plzeň Region in the area of the Pilsen Uplands. The summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and the temperature is 7–8.5 °C.

All data from the experimental plots and measurements were subjected to basic statistics. The statistic was performed for data containing infiltration rate in the first rainfall simulation and in the second simulation. The main objective in this case was to verify whether the change in soil water infiltration rate between simulations is statistically significant. For each location, the average infiltration rate in mm/min and the standard deviation were determined. Subsequently, the normality of the data was verified by the Shapiro-Wilk test (significance level α 0.05). Not all locations met the normality of the data (even after performing a logarithmic transformation of the data), therefore the Mann Whitney U test (significance level α 0.05) was used, which is appropriate in these cases. The same evaluation method was performed for soil moisture information.

RESULTS AND DISCUSSION

Locations with different soil texture were included among the experimental areas (Table 1). Soil texture fractions were analyzed and possible dependencies with infiltration rate and soil moisture were searched for.

Infiltration rate and its changes in relation to soil texture. The results show that the soil texture has a significant influence on infiltration rate. This is in agreement with the authors (Bloemen 1980; Wesseling et al. 2009; Yao et al. 2013) who did similar research.

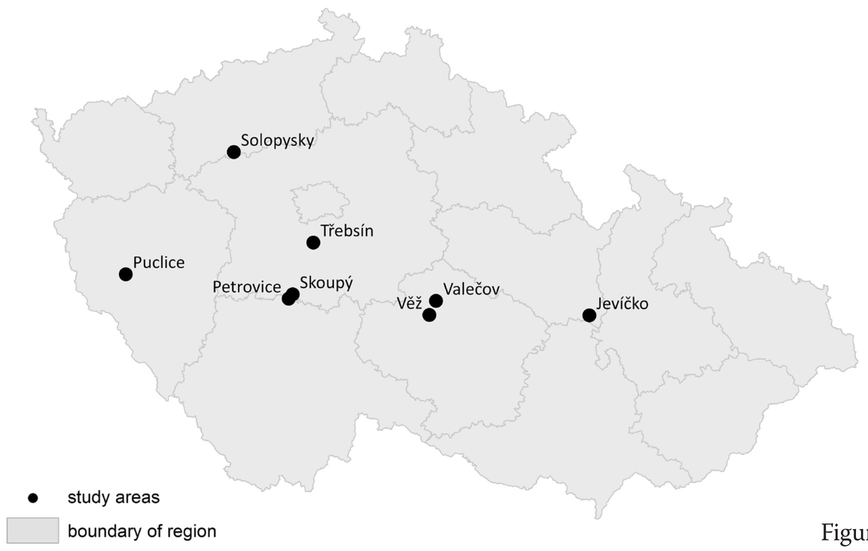

Figure 1. Map of the experimental areas

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Table 1. Basic soil characteristics of the experimental areas

Location	Soil classification (USDA – soil texture triagle)	Soil texture (%)			Content of C_{ox} (%)
		clay (< 0.002 mm)	silt (0.002–0.05 mm)	sand (0.05–2 mm)	
Třebsín	silt loam	9.16	53.98	36.86	1.21
Solopysky	clay loam	24.79	41.77	33.44	1.02
Jevíčko	silty clay loam	28.39	60.8	10.81	1.19
Věž	sandy loam	11.47	35.7	52.84	1.16
Petrovice	sandy loam	7.33	24.07	68.6	1.01
Skoupý	sandy loam	7.05	37.6	55.35	1.32
Valečov	loamy sand	9.33	8.2	82.48	0.98
Puclice	loam	11.03	44.0	44.97	1.49

USDA – The United States Department of Agriculture, C_{ox} – carbon oxides

According to our data, the amount of sand particles (0.05–2 mm) has the greatest effect on water infiltration rate due to changing soil moisture. This fact is clearly visible in Figure 2. The R^2 number for the trend line reaches the value of 0.8535, so it is a relatively strong dependence. For the other two soil texture fractions, the R^2 number reached lower values.

With the exception of one locality (Puclice), the results of the other localities are very close to the established trend. One of the main reasons why Puclice deviates the most from the established trend may be the carbon oxides (C_{ox}) content in the soil, which was the highest there (Table 1). Soils with higher organic matter content are able to infiltrate and retain more water than soils with less organic matter (Hudson 1994; Adamu & Aliyu 2012; Yao et al. 2013).

The rate of infiltration between rainfall simulations changed the most in the Jevíčko location, which has 10.81% sand particles. This is followed by the locations of Solopysky and Třebsín, where the content of sand is around 35%. On the other hand, the rate of infiltration changed the least at localities with the highest sand content, namely at the Valečov and Petrovice locations. This is most apparent in the case of Valečov, where there is loamy sand soil.

It is therefore evident from the results that due to smaller changes in the rate of water infiltration in sandy soils, a more constant surface runoff due to changing soil moisture can be expected in these soils. This is the case of the Valečov location, where the infiltration rate changed between rainfall simulations by only 15.64%. On the contrary, in soils with a low percentage of sandy fraction, there was a more

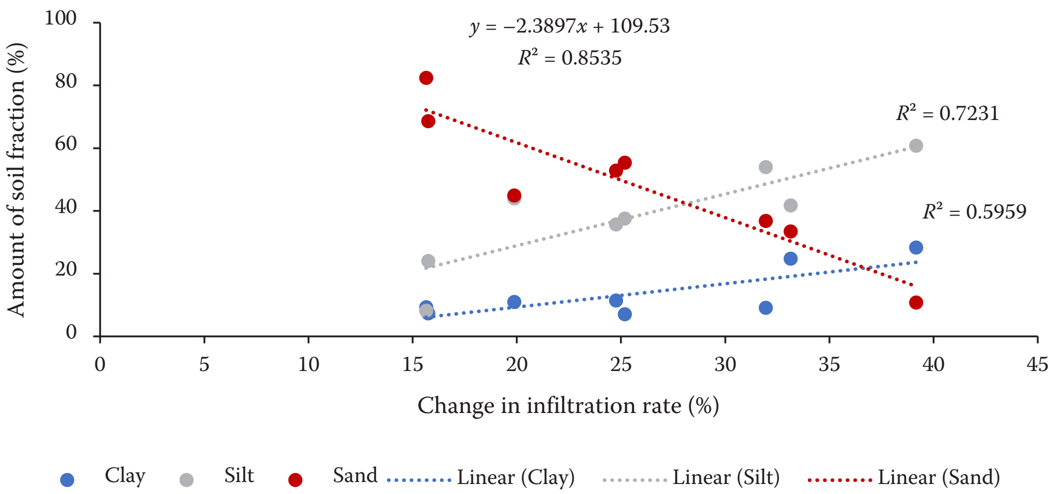

Figure 2. Relationship between infiltration rate and soil texture

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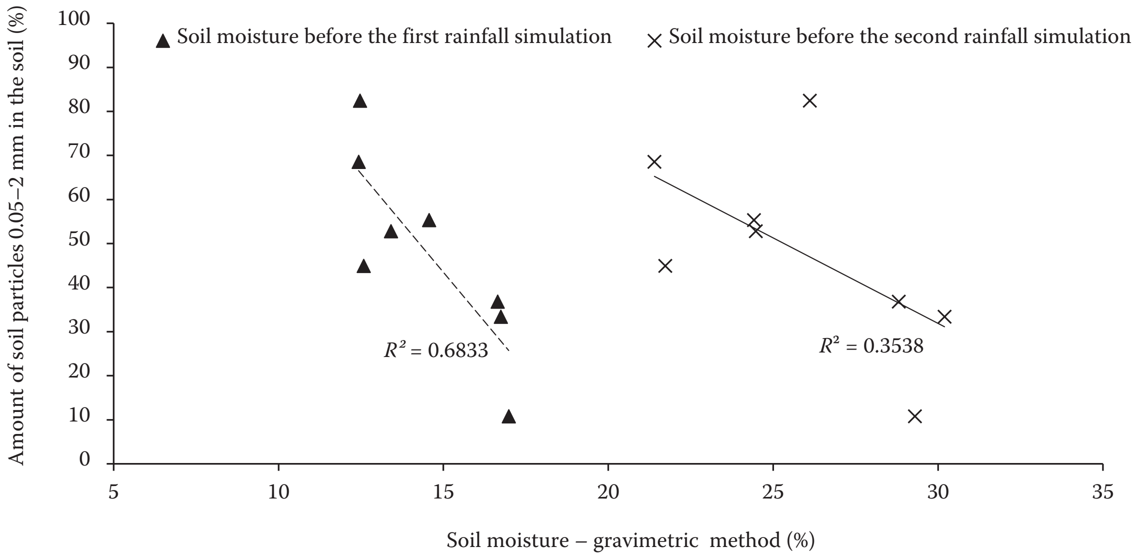

Figure 3. Relationship between soil texture and soil moisture

significant decrease in the rate of water infiltration. In the case of our results, the infiltration rate changed by 39.16% at the Jevíčko location (Table 2), which is a relatively significant change for the subsequent prediction of surface runoff.

As part of the research, various trends in initial soil moisture were also monitored. Figure 3 shows that soil moisture was on average higher in soils with a lower percentage of sand (0.05–2 mm) than in soils with a higher percentage of this fraction. Lighter soils with a higher sand content do not hold water as tightly and dry out faster (Gerard 1965; Oosterveld & Chang 1980; Cosby et al. 1984), which is also in line with our measured results (R^2 = 0.6833). The soil moisture results in Figure 3 may be affected by current weather at the time of simulation, especially the occurrence of the last natural rainfall (Pan et al. 2003) before measuring by the rainfall simulator. However, due to the relatively large number of measurements, this fact should not have a major influence on the established trend. The variation in initial moisture in the individual experimental plots is captured to some extent in the standard deviation of the average soil moisture (Table 2).

After the first rainfall simulation, the differences in soil moisture depending on soil texture (content

Table 2. Calculated results from rainfall simulator data

Location	Time period	Count of measurement	First rainfall simulation				Second rainfall simulation			
			Soil moisture before simulation		Infiltration rate		Soil moisture after the first simulation		Infiltration rate	
			(%)	SD	(mm/min)	SD	(%)	SD	(mm/min)	SD
Třebsín	2015–2021	20	16.64	3.64	0.087	0.028	28.8	3.98	0.064	0.03
Solopysky	2016–2021	20	16.74	3.79	0.069	0.014	30.2	2.53	0.045	0.012
Jevíčko	2015–2021	19	16.98	4.14	0.081	0.017	29.3	3.87	0.051	0.018
Věž	2017–2021	13	13.41	2.82	0.065	0.012	24.47	2.75	0.049	0.012
Petrovice	2015–2018	11	12.43	3.75	0.072	0.016	21.4	2.91	0.06	0.01
Skoupý	2015–2017	8	14.56	2.75	0.083	0.016	24.41	3.45	0.061	0.011
Valečov	2014–2017	9	12.47	3.21	0.063	0.01	26.11	4.28	0.053	0.009
Puclice	2015–2018	12	12.58	2.89	0.054	0.007	21.73	4.72	0.043	0.008

Soil moisture – soil water contents by mass; SD – standard deviation

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Table 3. Basic statistics from the measured date for infiltration rate and soil moisture

Location	Infiltration rate - average change between rainfall simulations						Soil moisture		
	Shapiro-Wilk test (*P*-value)		Mann Whitney U test (*P*-value)	(mm/min)	SD	percentage change (%)	Shapiro-Wilk test (*P*-value)		Mann Whitney U test (*P*-value)
	first RS	second RS					first RS	second RS	
Třebsín	1.10E-02	8.40E-02	1.54E-02	0.023	0.006	31.94	5.42E-01	4.29E-01	4.97E-08
Solopysky	8.80E-02	2.60E-02	2.88E-05	0.023	0.011	33.14	2.21E-01	2.47E-01	1.01E-07
Jevíčko	3.51E-01	1.90E-01	2.66E-05	0.030	0.008	39.16	8.67E-01	8.16E-02	1.36E-09
Věž	2.77E-01	3.15E-01	1.60E-02	0.016	0.006	24.76	4.87E-01	2.52E-01	2.84E-06
Petrovice	1.16E-01	6.81E-02	3.85E-02	0.012	0.007	15.74	8.40E-02	1.38E-01	1.13E-05
Skoupý	4.99E-01	5.81E-01	3.66E-02	0.021	0.007	25.18	6.14E-01	6.90E-04	9.31E-04
Valečov	9.21E-01	2.95E-01	4.16E-02	0.010	0.003	15.64	6.74E-02	3.17E-01	2.17E-05
Puclice	2.85E-01	3.93E-01	3.49E-03	0.011	0.005	19.87	3.05E-01	1.46E-01	8.11E-05

Soil moisture – soil water contents by mass; RS – rainfall simulation; SD – standard deviation; statistics test was performed for comparing data from the first and second rainfall simulation

of 0.05–2 mm soil particles) were less significant (R^2 = 0.3538). A similar trend is confirmed in the study of Vereecken et al. (2007).

The information from this sub-chapter can be used, for example, in environmental modelling. When modelling surface runoff without taking actual soil moisture into account, less accurate results can be expected for heavier soils compared to lighter, sandy soils due to larger fluctuations in water infiltration rate (Table 3). It would therefore be advisable to make some corrections (positive or negative) to the amount of surface runoff based on the current soil moisture for soils with a heavier texture. This recommendation is especially suitable for short-term rainfall-runoff models, where surface runoff from individual rainfall events is modelled.

Infiltration rate during the first and second rainfall simulation. In all experimental locations, it was confirmed that lower initial soil moisture (state before the first rainfall simulation) allows faster water infiltration than if the soil has higher soil moisture (state after the first rainfall simulation) (Figure 4).

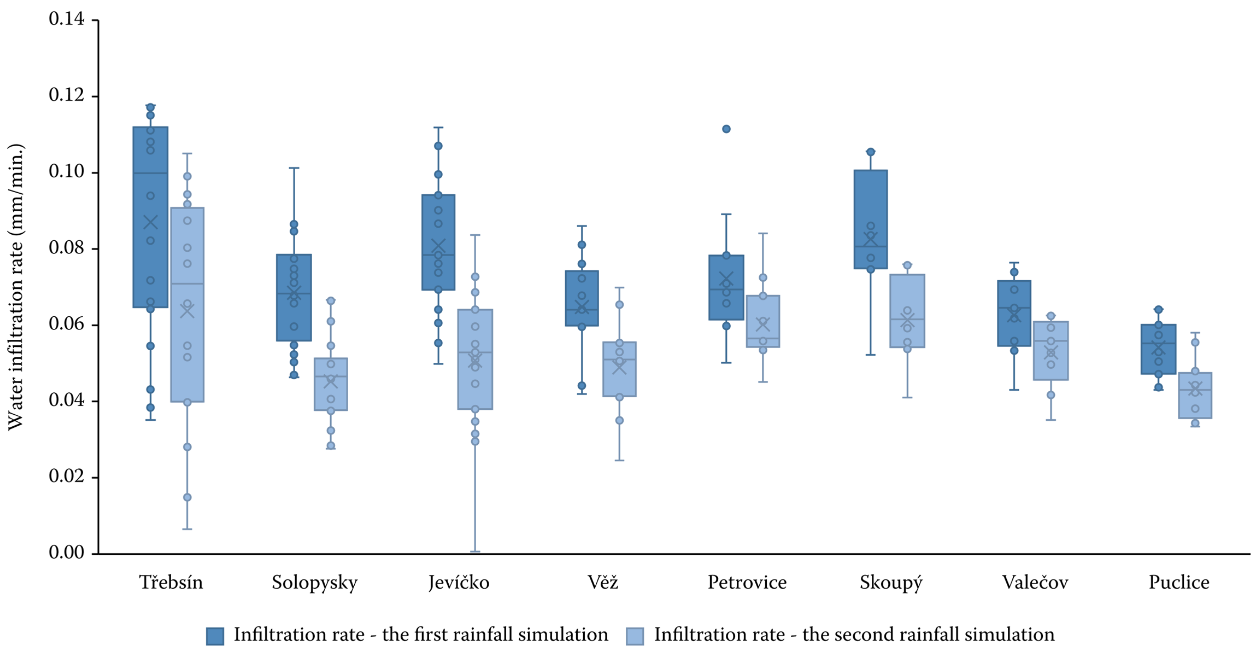

Figure 4. Water infiltration into the soil in the first and second rainfall simulations

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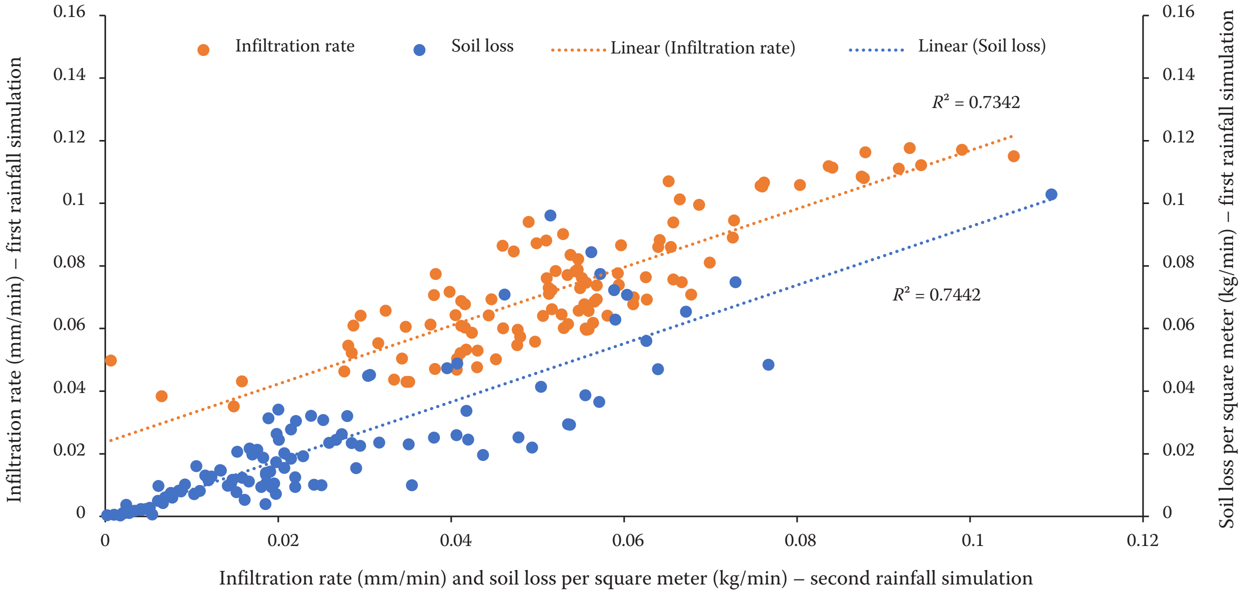

Figure 5. Results from rainfall simulator – differences between first and second rainfall simulation (infiltration rate and soil loss)

This is in line with Houser (2003), Steward et al. (2013), Matula et al. (2015) and others. Due to the method of rainfall simulation and preparation of the experimental area (Wischmeier & Smith 1978; Janeček et al. 2012) before the first simulation (loosening the top layer of soil up to 5 cm and then rolling it with a roller weighing 50 kg), the occurrence of a solid upper crust was prevented, which could affect the measurement, especially on heavier soils. The emphasis was also placed on the fact that there were no plant residues on the experimental plots, which could also significantly affect the measurements.

Infiltration rate in relation to soil loss. It is obvious that changes in infiltration rate affect the amount of surface runoff (Blanco-Canqui et al. 2002). This can in turn affect the amount of soil eroded. Due to the large amount of information obtained from the rainfall simulator, it was possible to look for the relationship between water infiltration and soil loss. Individual measurements are shown in Figure 5, specifically shows the average infiltration rate and soil loss from the rainfall simulator in one minute. When evaluating each parameter separately, it is possible to find certain dependencies between rainfall simulations, but when comparing the rate of soil water infiltration and soil loss, our data showed no significant relationships (various combinations were tried). It has not been confirmed that higher water infiltration means lower soil loss, which is consistent with, for example, Szabó et al. (2015).

This confirms the very well-known fact that soil erodibility is a more complex process than water infiltration. Infiltration rate is one of the parameters affecting soil loss, but several other parameters must be taken into account when modelling it, especially the energy of raindrops, which significantly increases the transport capacity of surface runoff (Vaezi et al. 2017). According to many studies (for example Kiani-Harchegan et al. 2019; Zambon et al. 2021;) soil loss increases with rainfall intensity and slope steepness (Sobol et at. 2017). In the case of water infiltration, this fact does not apply. Some studies (Wischmeier 1966; Kinnell 2016) claim that a higher slope means more surface runoff, others do not (Lal 1975; Liu et al. 2015; Jourgholami et al. 2020). The possible causes of this phenomenon are explained by e.g. Roose (1973). The relationship between slope and infiltration rate has different conclusions in a number of studies (see above). In our case, when the slope on the experimental plots was in the little variance of 5–10°, no significant influence on the infiltration rate is expected. This is confirmed by the study of Arjmand Sajjadi and Mahmoodabadi (2015) or Martínez-Murillo et al. (2013), where this issue is well described.

CONCLUSION

Information on the rate of water infiltration and its response to varying soil moisture is important and useful, especially in modelling erosion and hydrological

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processes. The results confirm that the infiltration rate changes due to changing soil moisture. This fact is most influenced by sand particles (0.05–2 mm). It is specifically stated that the more sand in the soil, the smaller the changes in infiltration rate (15.64% – location Valečov). On the contrary, in heavier soils, the rate of water infiltration changes by up to 40% (Jevíčko location). This means that more accurate data can be expected in surface runoff predictions in sandy soils if current soil moisture is not taken into account. The results also show that in all examined cases, the infiltration rate between rainfall simulations decreased. Therefore, it is obvious that different initial soil moisture can change the water regime of the soil. This fact subsequently affects other downstream processes. The results presented in the article are primarily applicable for the territory of the Czech Republic, possibly for the territory of Central Europe, or they may serve as a comparison for other areas.

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Publikace 10

Název

Evaluation of sediment barriers in relation to the trap of soil particles.

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Evaluation of sediment barriers in relation to the trap of soil particles

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Abstract: Water erosion and the subsequent sediment deposits can cause a number of environmental problems. The damage can be mitigated by means of sediment barriers. Their use is most often associated with the construction or protection of transport infrastructure. In some cases, they can also be used in forestry and agriculture. However, there is still a number of questions concerning sediment barriers regarding their proper function, efficiency and some implementation parameters. For these reasons, we decided to verify three types of sediment barriers. They were tested by simulated flooding at a flow of 5 and 10 L/s, always for a span of 25 min. All the tested barriers had a similar soil particle trap efficiency of about 90%. We assume that this result was due to some of our modifications to the sediment barriers and, above all, through the ensured run-off, where there were no structural failures within the barriers. Furthermore, it was also found, during the simulations, that the required sediment process of the eroded soil was not significantly affected by the size of the storage space. Therefore, it should be designed primarily with regard to the required amount of sediment and not to retain a significantly large volume of water.

Keywords: full-scale testing; silt-fence; soil bund; soil erosion; straw bale; trap efficiency

Land disturbances caused by human activities, such as construction, development, or agriculture, typically involve the removal of the vegetation cover and topsoil and cause soil disturbances. (Vitousek et al. 1997). As a result, the storm water run-off and erosion rates are significantly increased (Procházková et al. 2020). The subsequent erosion and sediment transport have both onsite and offsite economic effects. The erosion and soil loss, along with negative economic impacts, cause uncontrolled water and sediment run-off which degrades the surrounding environment. If the sediment gets off the site, watercourses, water ways and other objects can become clogged (Morgan 2009). The sediment-laden discharge can increase

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the turbidity (Kirk 1985; Ryan 1991), decrease the flow capacity, and provide a mode of transport for other pollutants (Alekseevskiy et al. 2008), which affects the amount of sunlight falling on aquatic plants (Isobe & Matsuno 2008) and deteriorates the living conditions of other aquatic animals (McDowell & Wilcock 2008).

In order to prevent soil wash-out outside the affected plot of land, sediment barriers have commonly been used abroad, which have become the basic protection measure most commonly used on construction sites (Schussler et al. 2021). However, they are also used in other sectors, such as protection in the transport infrastructure, in forestry after fire damage and in agriculture (Robichaud al. 2008; Donald et al. 2016). Sediment barriers have the character of a line barrier, which can be created from different types of materials: wheat straw, soil and stones, urethane foam or woven and non-woven geotextiles (Donald et al. 2013, Whitman et al. 2018). The main purpose of sediment barriers is to trap the washed-out sediment released by torrential rain (Schussler et al. 2021; Whitman et al. 2021) and to interrupt the surface run-off (Boardman et al. 2019). Due to the interruption of the run-off line, the flow velocity is reduced and the gravitational sedimentation is enhanced in front of the formed barrier (Donald et al. 2016).

However, some questions about the operation of sediment barriers still remain open. The issue of the efficiency and structural stability of barriers in operating conditions is still being addressed in expert publications (Bugg et al. 2017a; Whitman et al. 2018). Various shape installation methods on a plot have been designed and tested (Featherston et al. 2004; Zech et al. 2008). Moreover, the possibilities of burdening and draining sediment barriers have been determined, which should reduce the frequency of their failures (Donald et al. 2016; Whitman et al. 2021). Therefore, we have also focused on some of these issues, and the results and experience from our full-scale plot experiments are described in this article. The main objective of the study is to increase the awareness of mobile sedimentation barriers and to enrich this area with new information and knowledge gained during several years of research. The article is mainly focused on the ability of various sedimentation barriers to trap washed-out sediment. The size of the storage space has been modified over the years in order to test whether its extent affects the amount of sediment trapped. We do believe that the research focused on sedimentation barriers has a considerable potential and the information provided in the article can contribute to their greater use in practice.

MATERIAL AND METHODS

Tested barriers and their parameters. The testing of anti-erosion sediment barriers (Figure 1) was

Figure 1. Tested sediment barriers

1 – silt-fence; 2 – straw bale barrier; 3 – soil bund wit vegetation; 4 – trapped sediment

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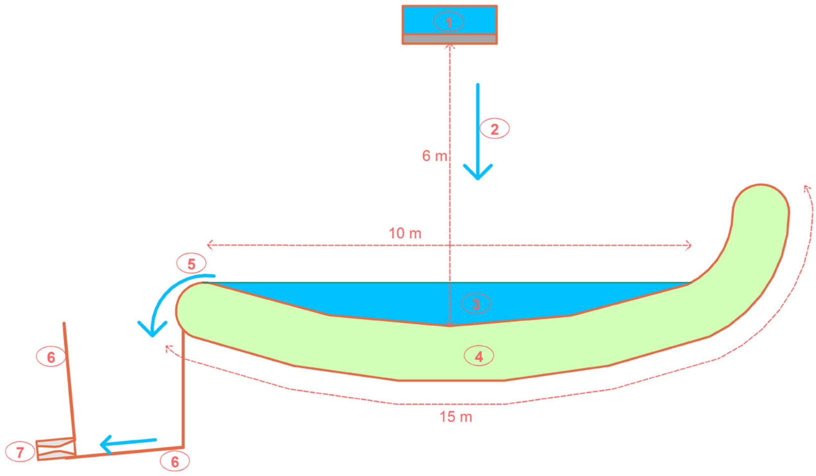

Figure 2. Testing method of sediment barriers
1 – overflow flume, 2 – direction of inflow onto the sediment barrier; 3 – storage space; 4 –sediment barrier; 5 – lateral run-off over the edge; 6 – plastic barriers directing run-off; 7 – Parshall flume

carried out from 2017 to 2021. More information is included in Electronic Supplementary Material (ESM). The first of the tested measures was a soil bundle with vegetation, which was created by building gradual levels of soil bunds and soil compaction. Its height reached 0.45 m and width in the foundations was 1.2 m. The soil bundle was made in a convex shape. In order to stabilise it, the entire surface was sown with a grass mixture, including a 1.5 m long space in front of it. The grass mixture consisted of perennial ryegrass (*Lolium perenne*), red fescue (*Festuca rubra rubra*) and Italian ryegrass (*Lolium multiflorum* Lam.) The second tested barrier was the silt-fence sediment barrier. The excavation depth for laying it was at least 0.15 m and the woven fabric was laid in a U-shape. Thus, approximately 0.4 m of fabric's length was anchored in the ground after backfilling and compaction of the soil. The remaining part of the fabric, above the ground, was 0.65 m long. The support posts were chosen to be made of wood having parameters 0.05 × 0.05 m and a length of 1.3 m. The fabric was attached to them using a stapling gun. The last of the verified measures was a straw bale barrier. The individual packages had a size of 0.4 × 0.5 × 0.6 m and were tightly placed in a trench. Its width corresponded to the size of the package and was set 0.1 m deep. Stabilisation was again carried out by means of a wooden post (0.05 × 0.05 m) with a length of 0.8 m, and only 0.1 m protruded after ploughing it into the package. To make the barrier work properly, the upstream side of the barrier was included up to the maximum height of the water level swell. The barrier made of straw bales, thus, became minimally permeable and no undercutting occurred. All the above-mentioned sediment barriers were built with a length of 15 m in the shape of the letter J. The storage space was created by the inclination of the barrier against the slope. The size of the storage space was then subject to an elevation between the centre and the edge of the sediment barrier. In the individual years, the elevation in the range of 0.0–0.2 m was verified. The burdening of the barrier by the water column itself was further increased by the height of 0.05–0.1 m to overcome the edge of the barrier by the run-off. Measurements took place twice a year in spring and autumn to test the barriers before and after the occurrence of erosion-prone precipitation. The data from the individual years were subjected to basic statistics – arithmetic mean, median, standard deviation. Subsequently, based on the normality of the data assessed by the Shapiro-Wilk test, the hypotheses were tested using a one-way analysis of variance (ANOVA) or a paired *t*-test. The significance level α was set to 0.05 in all the tests.

Testing method of sediment barriers. The testing of the mobile barriers (Figure 2) consisted in their controlled flooding with surface run-off with an intensity of 5 L/s and 10 L/s always for the time-span of 25 min. The intensity and duration of the simulation were chosen on the basis of the study by García et al. (2015), which, however, addressed other types of sediment barriers. The surface run-off itself was developed using sludge pumps with a known flow, which were drained into an irrigation trough with a volume of 224 L and an overflow edge length of 1.4 m. Its function was to direct the turbulent flow from the pumps to such an extent that the water flowed onto the soil surface. The distance of the irrigation trough from the tested sediment barrier was 6.0 m. After filling the defined storage space of the sediment barrier, a lateral run-off occurred over the edge of the barrier. This was guided into a Parshall flume

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by a system of plastic barriers with a slope of 1%, where the current value of the flow was read and recorded every fifteen seconds. The efficiency of the trapping eroded material by the individual sediment barriers was evaluated on the basis of a differential model determining the volume of the erosion furrows and deposited sediment. Surface measurements by 3D laser scanning were the basis used to create the difference model, which recorded the condition of the soil surface (between the irrigation trough and the sediment barrier) before flooding the sediment barriers, after simulating the flow of 5 L/s and after simulating the flow of 10 L/s. A Leica ScanStation P40 laser scanner (Leica Geosystems, Switzerland) was used for the scanning. It has a 360° × 270° field of view, whose accuracy of measuring the distance is 2 mm + 10 ppm and measuring angle is 8“. Maximum scanning range is up to 270 m (reflectance of 18%). The scanning rate is up to 1 million points per second. The scanner is equipped with a dual axis compensator with accuracy 1.5“. The scanning was carried out at 12 mm per 10 m resolution from one position.

Experimental area. The study area is located in Central Bohemia (Czech Republic) at the experimental station of Hovorčovice (226 m a.s.l.). The climate is warm and moderately dry, with an average annual temperature of 8.5 °C and annual precipitation of 500–600 mm. The geographical coordinate system is 50°10'56.520''N, 14°31'54.914''E (Figure 3). The soil type chernozem was classified on all the experimental plots – with a Main Soil Unit of MSU 01. Based on the soil survey, it can be stated that the basic physical-chemical properties are similar in terms of the soils for the individually tested plots and, therefore, the tested plots are comparable. The upper horizon of all the compared sites shows a texture type, a structure typical of silt loam soil. The basic soil properties: 1.72% total oxidisable carbon (C_{ox}); humus of 2.97%; total nitrogen (N_{tot}) of 0.21; C/N ratio of 8.4. The top soil layer is up to 30 cm (the soil texture: < 0.001 mm, 22.0%; 0.01–0.05 mm, 50.1%; 0.05–0.25 mm, 8.0%; 0.25–2.0 mm, 1.3%). The plots for the tested sediment barriers were selected particularly for their uniform slope of 8.5%.

RESULTS AND DISCUSSION

Despite the fact that sediment barriers have been used abroad for decades, their operational efficiency, proper function and other possible methods of installation and draining are still being addressed. Previously used laboratory and small-scale testing have failed to adequately simulate the surface run-off and to quantify the sediment retention efficiency in relation to structural stability of the barrier. Therefore, more and more experiments are currently beginning to appear that evaluate sediment barriers in operational and pilot conditions (Risse et al. 2008; Bugg et al. 2017b). These conditions were also simulated in our experiments. However, even this method had its limits due to the complexity and possibilities of the verification. Therefore, the results do not take into account the positive effect of the cascade installation of sediment barriers and the occurrence of further erosion on the plots of land located below the sediment barrier.

Sediment barrier efficiency in terms of trapping eroded soil. Within the first hypothesis, the

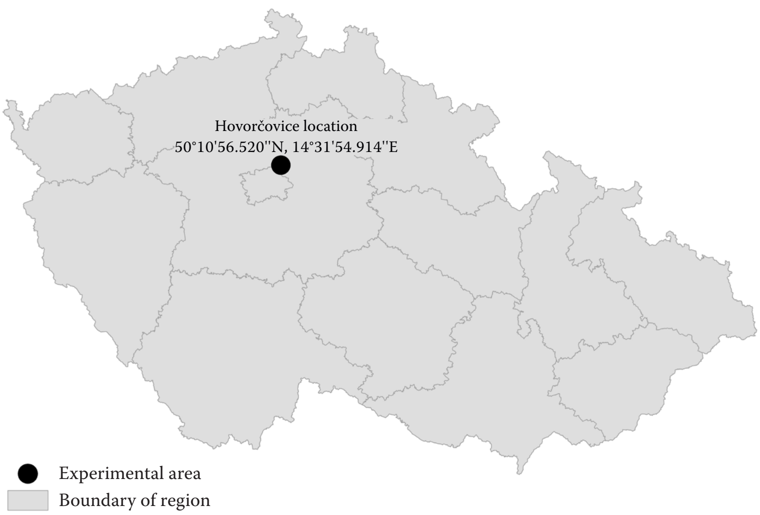

Figure 3. Location of the experimental area

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aim was to verify whether the results show a difference between the efficiency of the individual types of sediment barriers. That is, whether any barrier was demonstrably more efficient and trapped a relatively larger amount of soil particles. When running checks according to the Shapiro-Wilk test, the data were found to have a normal distribution. The arithmetic mean and median of all the sediment barriers were identical at around 90% efficient. The values of the standard deviations, which did not exceed 0.05, were also relatively low. The measured data were subjected to a statistical one-way ANOVA test, when the *P*-value reached 0.64. Therefore, no difference in efficiency was demonstrated between the individual types of sediment barriers (Table 1).

Silt-fence efficiency. Similar research with silt-fence sediment barrier was carried out by Bugg et al. (2017a), who verified and tested three possible installation methods. Our results it is possible to compare only with the two excavation methods of the silt-fence installation. The first type of installation, the ALDOT Trenched Silt Fence, trapped 86.6, 86.7 and 74.8% of the sediment in the individual experiments. Within the second type of installation, the AL-SWCC Trenched Silt Fence installation, the efficiency was even higher at 90.5, 91.0 and 90.0%. Another comparison is offered in the article by Robichaud and Braun (2002), who used a silt-fence as an economical option of measuring hill slope soil erosion. In the first year, the measures were evaluated after each precipitation-run-off event. The average efficiency value was found to be about 93%. In the second year, the individual precipitation-run-off events were no longer checked, only the total value for the season was checked. A 92% success rate was established in this case. Likewise, Kouwen (1990) states that a sediment trap efficiency of 90% and higher can be achieved. Our silt-fence barrier efficiency results, therefore, appear to be similar to these authors. Some authors state slightly lower values. Barrett et al. (1995) measured trap efficiencies in a range of 68–90% and Wishowski et al. (1998) measured trap efficiencies in a range of 69–81%. However, all the above-mentioned values are very favourable in terms of trapping wash-out sediment.

Straw bale barrier efficiency. On the other hand, in the case of another barrier from straw bales, our efficiency results were higher than for other authors. Robichaud et al. (2019) established that the straw bale barrier traps less than 50% of the total volume of eroded material. However, even this value is not considered stable either and its decline during the season is described. Therefore, the sediment barrier needs to be checked and repaired relatively more often. Poché and Sherwood (1976) also establish lower efficiencies, whose study evaluated sediment barriers in operating conditions, where a total of 9 barriers spaced 30.5 m apart were monitored. The straw bale barriers were efficient in a range of 28–98% within the first rainfall. On average, it reached 57%. Within the second rainfall, three measures were already damaged, the others were found to be in the range of 19–50%. Similarly, Johnson (2003) states that straw bales have an average efficiency of trapping medium and coarse sediment particles, and that they are generally not very effective in terms of trapping fine mud or clay particles in the run-off. The location of the barrier is undoubtedly reflected in the efficiency of trapping individual soil fractions. Therefore, the difference between our results and the results of other authors may arise due to the way the sediment barrier is implemented and the location during testing on the site, i.e., on the plot. During the installation, the upstream side was filled with loose soil and then subsequently compacted with a cylinder weighing 60 kg up to the maximum considered level in the

Table 1. Efficiency of the individual types of sediment barriers and the statistical evaluation

Type of sediment barrier		Arithmetic mean	Median	SD	Shapiro-Wilk test	One-way ANOVA test	Paired *t*-test
		(%)			*P* value α = 0.05		
Soil bund with vegetation	5 L/s	90.1	90.0	0.027	0.11	0.64	0.71
	10 L/s	90.3	90.5	0.028			
Silt-fence	5 L/s	91.2	90.5	0.030	0.16		0.63
	10 L/s	90.9	90.0	0.025			
Straw bale barrier	5 L/s	89.8	90.0	0.023	0.98		0.32
	10 L/s	91.1	91.5	0.041			

SD – standard deviation

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storage space. It is the mounding of excavated soils of the upstream side that proves to be a key factor. Without its implementation, there is significant flow leakage and the barrier partially loses its function. Undoubtedly, the different method of drainage also affected the results. After filling the storage space, the water did not flow over the barrier, but flowed out freely at its edge. This area was stabilised to prevent further erosion by the discharge from the sediment barrier. The possibility of lateral drainage was based on the different positioning of the sediment barrier. This was verified on a straight slope and not in a concentrated flow path as in the stated studies.

The efficiency of the soil bund with vegetation. Comparing the result for the anti-erosion soil bund with other studies is relatively complicated due to the different construction and soil-climatic conditions. Therefore, we consider the study of Amare et al. (2014) to be most relevant, as it assessed a soil bund with different types of vegetation cover. These were implemented on experimental plots with an area of 180 m^2 (6 × 30 m). They had a longitudinal slope for draining excess water of 2% and a 10 m interval was kept between the individual bunds. The highest anti-erosion efficiency was found to be in the combination of a soil bundle with elephant grass (*Pennisetum purpureum*), where the soil loss was reduced by 63.5%. For the other two barriers with vegetation cover, the soil loss was reported to be only slightly lower. The soil bund in combination with Vogel's tephrosia (*Tephrosia vogelii*) reduced the soil loss by 58.0% and jaraguá grass (*Hyparrhenia rufa*) by 56.5%. The main reason why our results are higher may be the different realization of the sediment barrier on the plot (contour versus with longitudinal slope). The question of how big this difference can be is addressed in the study by Wolka et al. (2018). It compared the efficiency of different types of sediment barriers due to their location on the plot of land. For a soil bund with a 1% longitudinal slope, an average value of 46% in terms of the reduction in the soil loss is stated, meanwhile, in a soil bund with a contour orientation, it is 60% on average. In another relatively similar sediment barrier, Fanya juu terraces, this difference was found to be even greater than 26%. In both cases, the soil barriers were without vegetation cover. We, therefore, assume that the combination of the contour location and vegetation cover had a positive effect on the efficiency of the barriers that we set.

Impact of the simulated flow in terms of trapping the eroded soil. Another hypothesis addressed whether the efficiency of the barriers would change with the size of the surface run-off, with the individual sediment barriers being flooded with flows of 5 and 10 L/s. A paired *t*-test was used for this purpose. A *P* value of 0.71 was set for the soil bund, 0.63 for the silt-fence and 0.32 for the straw bale barrier (Table 1). Thus, it was not possible to prove that the intensity of the surface run-off had a demonstrable effect on the efficiency of soil particle trapping for any of the sediment barriers (Table 1).

When compared to other studies, the flow rate chosen in our study was comparable. Bugg et al. (2017b) chose 6 L/s, García et al. (2015) chose 5, 7.5 and 10 L/s, Whitmann et al. (2019) chose 6.2 L/s. In some studies (Robichaud et al. 2008; Gogo-Abite & Chopra 2013), the authors used various rain simulators instead of pumps to create surface run-off, which is another way to verify sedimentation barriers. However, the disadvantage is usually a smaller experimental area.

We assume that, in our case, the main influence on this result is the position of the inflow on the sediment barrier and the amount of eroded material in the storage space. Within the measurement, the overflow trough and, thus, the inflow was directed to the centre of the sediment barrier. At this point, during the collision with the barrier and through the influence of the accumulated water, there was a significant reduction in the drag speed, at which the eroded soil sedimented. Even at an increased inflow of 10 L/s, the deposited material was not carried beyond the edge of the barrier to the discharge. This could only happen under two conditions. Firstly, if the storage space was significantly filled with eroded material and secondly, if the inflow was located closer to the edge where the discharge from the sediment barrier occurs.

A similar result is described by García et al. (2015), only on the parameter of the total solids concentration. In the verified sediment barriers, this study did not show a strong relationship between the flow and the total solids concentration under the tank.

Impact of the storage space in relation to the efficiency of the soil particle trapping. The third hypothesis assessed the effect of the size and volume of the storage space on the efficiency of the soil particle trapping regardless of the type of sediment barrier used. Whitmann et al. (2021) states that there are very few studies on design modifications. Therefore, we tried to verify different sizes of storage spaces by adjusting the elevation between the centre

https://doi.org/10.17221/48/2022-SWR

and the edge of the sedimentation barrier. Certain information and recommendations regarding the construction solution can be found in the manuals and publications of individual US states (TDEC 2012; AL-SWCC 2014; NCDOT 2015; Lake 2016).

In our case, the size of the storage space increased in the individual years in intervals of 5 cm. The determined values of the soil particle trapping efficiency had relatively the same arithmetic mean, median and standard deviation. Using the one-way ANOVA statistical test, a *P* value of 0.75 was calculated, thus no significant difference was found (Table 2).

The size and especially the volume of the storage space has a direct effect on the resulting run-off from the sediment barrier. Thus, the smaller the storage space, the sooner the run-off occurs at the edge of the sediment barrier. Surprisingly, in the case of the trapping and eroded material, the same principle was not confirmed during our measurements. The amount of eroded material was constant of around 90% regardless of the size of the accumulation. Even with a contour orientation (plane 0 cm), the sedimentation occurred at the moment when the inflow with the eroded material reached the barrier. We noticed a certain difference in terms of distribution only in the form of the sediment between the barrier of the soil bund with the vegetation and the other two barriers, i.e., silt-fence and straw bale barrier without vegetation. In the soil bund, the 1.5 m long storage space was covered with a grass mixture, where the sedimented soil particles had a rather elongated shape in the inflow direction. On the contrary, in the case of the silt-fence and the straw bale barrier, the sedimentation occurred only as a result of limiting the inflow and, therefore, had a longitudinal shape identical to the direction of the barrier. We therefore assume that the importance of the size of the storage space will only become apparent with a larger amount of eroded material and the number of erosion-runoff events. Even a relatively small storage space, on the condition that the sediment is regularly removed, can reliably fulfil the required anti-erosion function. At the same time, a lower probability of structural failures can be expected. However, we intentionally avoided determining the exact size of the storage space, this must depend on the conditions on the plot of land, the source area size (Bugg et al. 2017b), slope (Gogo-Abite & Chopra 2013), the requirement for the amount of soil trapped, etc.

The size of the storage space in relation to the drainage of the sediment barrier was addressed by the work of Donald et al. (2016) and Whitman et al. (2021). They evenly placed the overflow to a height of 0.46 m, which was to drain excess water and relieve the burdening of the sediment barrier silt-fence. In both studies, the sediment trap was more than 90%, i.e., approximately the same as in the case of the barrier without a weir. In our measurements, the sediment barriers were not burdened with such a high water column. To determine the height of the column at the lowest point of the barrier, it is necessary to add an increase in the range of another 5–10 cm to the basic height of the storage space (height between the centre and the edge). The flowing water had to overcome this height in order to flow freely from the edge of the sediment barrier.

Influence of the measurement terms regarding the soil particle trapping efficiency. The last hypothesis asked whether there is any influence concerning the verification term regardless of the type of the barrier. The effectiveness of sedimentation barriers is influenced by a number of indicators, such as the water retention time, barrier length, but also by the type of soil found in the given area or water temperature (Fennessey & Jarrett 1994; Waters 1995).

After having arranged the measured data, it was apparent that the values of the arithmetic mean and median are higher within the autumn verification

Table 2. Efficiency of the sediment barriers in relation to the size of the storage space

Years of measurements	Storage space (elevation between the centre and edge of the sediment barrier)	Arithmetic mean (%)	Median (%)	SD	Shapiro-Wilk test (P value α = 0.05)	One-way ANOVA test (P value α = 0.05)
Y1	plane 0 cm	90.2	90.0	0.032	0.40	
Y2	height elevation 5 cm	91.5	91.5	0.035	0.36	
Y3	height elevation 10 cm	90.5	90.5	0.024	0.61	0.75
Y4	height elevation 15 cm	90.7	91.0	0.021	0.87	
Y5	height elevation 20 cm	90.0	90.0	0.032	0.65	

SD – standard deviation

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Table 3. Sediment barriers efficiency in relation to the term of the measurements

Term of measurements	Arithmetic mean	Median	SD	Shapiro-Wilk test	Paired *t*-test
	(%)			*P* value α = 0.05	
Spring measurement	88.7	89.0	0.019	0.05	2.79E-07
Autumn measurement	92.5	92.0	0.024		

SD – standard deviation

date. This did not apply to the standard deviations, which remained relatively low for both terms. The normality of the data distribution assessed by the Shapiro-Wilk test had a threshold value of 0.05. Nevertheless, a parametric paired *t*-test was used to assess the probability. The resulting value reached a *P* value of 2.79E-07, thus, the difference between the spring and autumn simulations was statistically significant (Table 3). The results of the efficiency of the individual terms are shown in Figure 4.

We assume that the main reason for the higher efficiency of the autumn term is generally the better tightness of the barriers. In the case of a silt-fence sediment barrier, the individual textile pores are clogged with eroded material during the season. This effect is also described by Whitman et al. (2021) and Bugg et al. (2017a). At the straw bale barrier, the higher tightness is due to the overall compaction of the embankment, on which a protective and less permeable soil crust is frequently formed. Moreover, the principle of compaction undoubtedly also applies in the case of soil bund, which is further supported by the higher quality and density of the grass in the autumn period. A favourable effect of grasses with fast growth and high biomass production is also confirmed by the study of Amare et al. (2014).

CONCLUSION

Sediment barriers have a specific position and use within anti-erosion protection. On plots threatened by erosion, they interrupt the surface run-off and trap soil sediments. Their use and exploitation are most often associated with construction sites, linear transport structures, but they are also beginning to find their application in the agriculture and forestry sectors. In the past, it was not recommended to place sediment barriers in places with more concentrated flow, where they are significantly burdened and there is a risk of damage. However, even in this direction, some changes can be expected thanks to new findings. Sediment barriers are beginning to be equipped with various types of discharge devices that regulate the amount of water retained. However, the parameters of the storage spaces and their efficiency

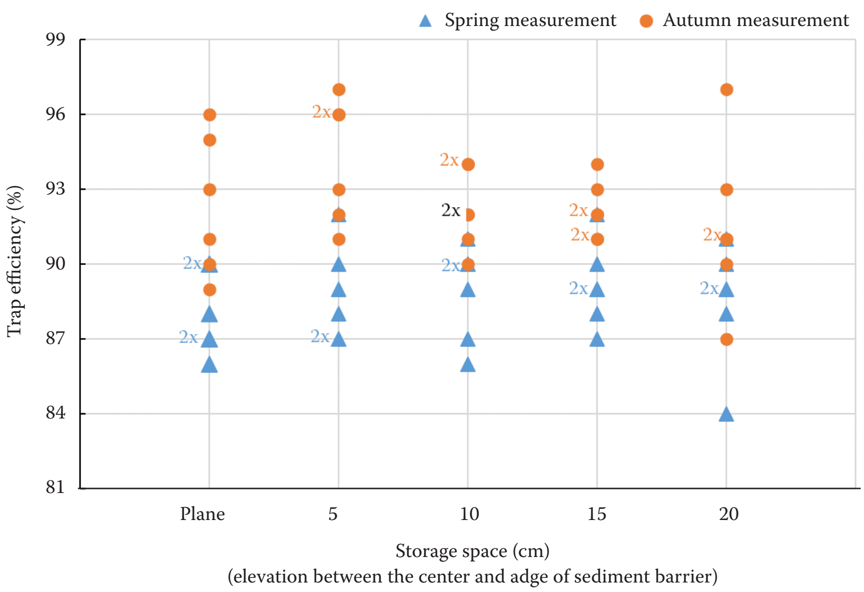

Figure 4. Soil particles trap efficiency in relation to the term of the simulation

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of trapping eroded soil particles are also closely related to this. Therefore, our research focused on verifying the anti-erosion efficiency of sediment barriers and their basic installation parameters.

The sediment process itself, with a high efficiency of about 90% was recorded for all types of barriers: silt-fence, straw bale barrier, soil bund with vegetation even with a minimum size of the storage space. On the contrary, the simulated inflow with a capacity of 5 L/s and 10 L/s had no effect on the resulting efficiency. The correct function of the barrier is therefore limited only at the moment when the trapped sediment begins to reach the edge into the run-off area. This can also speed up an inappropriately oriented concentrated inflow to the side where the sediment barrier is drained.

Surprisingly, the autumn simulation term was slightly better than the spring one in terms of the efficiency results. This is generally due to the lower permeability of the sediment barriers. However, this result would not be achieved without regular maintenance and repairs. The silt-fence barrier required relatively little maintenance work, and this is, in our opinion, one of the reasons why it is considered by most authors to be the most effective. On the contrary, barriers close to nature have a worse position in this respect, lasting approximately 1–2 years on the plot. The benefits of their use will only become apparent upon removal, when the material from which they are made usually remains on the place.

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Estimating the curve number for conventional and soil conservation technologies using a rainfall simulator

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Abstract: The aim of the article was to verify the curve number (CN) values given in the National Engineering Handbook (NEH) methodology, whether they really correspond to all wide-row crops. The tested crops were maize, hops and potatoes grown using conventional and soil conservation technologies. All these crops are classified as wide-row crops, but they are very different in terms of the cultivation process. The basis for the calculation of our CN values were field measurements carried out using a rainfall simulator within the time span from 2014 to 2020 on the soil corresponding to hydrological group B in two repetitions: naturally dry soil corresponding to an ARC II curve and saturated soil corresponding to an ARC III curve. The results show that our calculated CN values for the conventional cultivation of wide-row crops are, in principle, the same as the CN values given in the NEH methodology. On the contrary, a certain difference was recorded in the soil conservation technologies with plant residues on the surface, in the case of naturally dry soil. Lower CN values are clearly seen in the technologies of no-till maize, strip-till maize and hops with catch crops, which was confirmed by the statistical tests, probably due to the interception and surface roughness.

Keywords: cover; row crops; soil degradation; surface runoff; residue tillage practice

Mathematical models (Amutha & Porchelvan 2009) are usually used to evaluate the amount of surface runoff. Some of the models are based on the curve number method, which is currently one of the most often used methods (Hawkins et al. 2009). Some examples of these models include SWAT (Soil and Water Assessment Tool) (Gassman et al. 2014), EPIC (Environmental Policy Integrated Climate) (Williams 1990), SWIM (Soil and Water Integrated Model) (Krysanova et al. 2000), AGNPS (AGricultural NonPoint Source) (Young 1989), etc. The curve number (CN) method is a procedure for estimating the streamflow volume generated by large rain storms, which was developed in the 1950s by the Soil Conservation Service in the USA (Cronshey 1986). The method is widely accepted because of its simplicity for surface runoff prediction all over the world (Ponce & Hawkins 1996), with the Czech Republic being no exception, as this methodology was implemented by Janeček et al. (2002). Basically, only two parameters are required for the surface runoff prediction (Ponce & Hawkins 1996), i.e., the initial abstraction coefficient (λ) and the potential maximum retention (S) expressed in terms of the curve number. Of course, the curve number includes the soil type, antecedent runoff condition, land use and cover (Hawkins et al.

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2009). At first glance, the methodology often combines relatively different technologies for establishing agricultural crops. Under one group of crops and the method of "treatment" (thus, also the CN number), permanent crops with a width of inter-rows of up to 3 m, crops grown in variously modified ridges shapes, as well as classic wide-row crops which are commonly grown are included. For this reason, we wondered whether one CN number for all crops was really reflective for all these crops. At the same time, a further discrepancy may occur when crops are combined with soil conservation technologies. It is common knowledge that these technologies reduce the surface runoff and erosion (Wischmeier & Smith 1965; Vanmaercke et al. 2011). However, is this method of treatment with crop residue for a mulching technology on the land, the establishment of crops with the catch crop and various other soil shaping technologies really telling in the methodology? The aim of this article was to verify the reported CN values in the National Engineering Handbook Hydrology (NEH) methodology part 630 Hydrology (NRCS 2004), whether they correspond to our determined values from measurements for individual wide-row crops. Simultaneously, another objective was to statistically verify whether the specified CN values for conventional and soil protective technologies are demonstrably different.

MATERIAL AND METHODS

The research dealing with the curve number values for various crops was carried out between 2014 and 2020. In total, three typical crops (maize, hops, potatoes) were verified in the Czech Republic. We have chosen hops for the maximum width of the inter-row spacing of 2.7 m, potatoes for their cultivation in ridges and maize due to the fact that it is the most frequently cultivated crop from the wide-row crops. Locations that are typical for the crop due to their soil-climatic conditions were selected for the verification. The locations of the experimental plots are shown in Figure 1 and their basic soil characteristics are in Table 1.

The experimental areas: (1) Víska u Jevíčka (maize) – the study area is located in Moravia. The summer climate is warm, dry to slightly dry with an average annual temperature of 8.4 °C and an annual precipitation of 650–750 mm. The average altitude is 360 m a.s.l.; (2) Solopysky (hops) – the study area is located in Central Bohemia. The typical summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and has a temperature of 7–8.5 °C. The average altitude is 300 m a.s.l.; (3) Věž (potatoes) – the study area is located in Vysočina (i.e., the Highlands). The summer climate is mild to slightly cold, slightly dry with an average annual temperature of 7.2 °C and an annual precipitation of 600–750 mm. The average altitude is 547 m a.s.l. The basic soil characteristics are listed in Table 1.

The verified technologies were:
(a) Maize conventional cultivation
(b) Maize strip tillage
(c) Maize no tillage
(d) Hops conventional cultivation
(e) Hops with catch crops

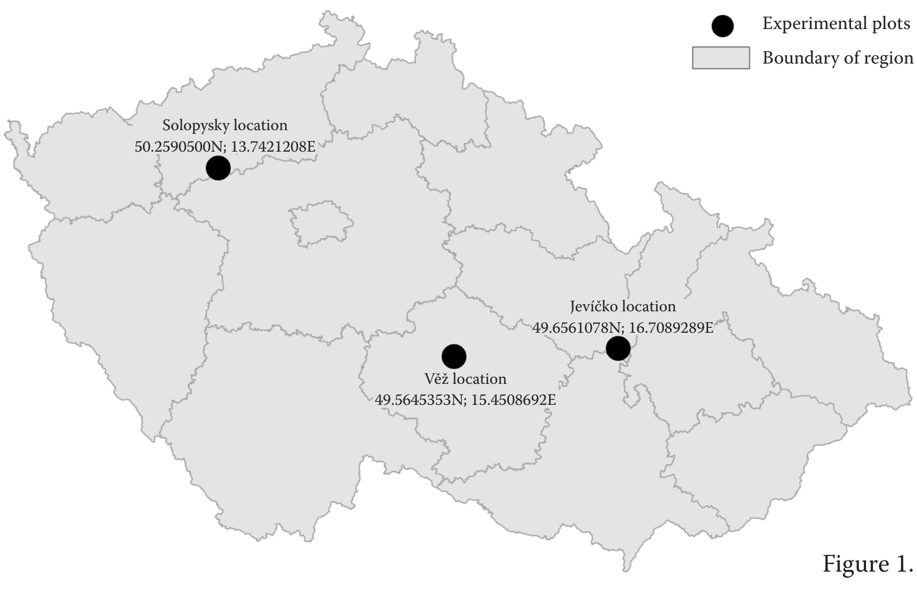

Figure 1. Map of the experimental areas

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Table 1. Basic soil characteristics of the experimental areas

Location	Agricultural crop	Soil classification	Soil texture	Division of soil texture (%)				Slope of the experimental plot (%)	Hydrologic soil group	Oxidisable carbon	Humus	Total nitrogen	Oxidisable carbon/total nitrogen
				< 0.002 mm	< 0.01 mm	< 0.05 mm	< 0.1 mm			(%)			
Jevíčko	maize	Haplic Luvisols	silt loam	22.7	34.8	75.6	89.1	11	B	1.25	2.2	0.15	8.3
Solopysky	hops	Luvic Cambisols	silt loam	23.8	36.5	66.7	84.4	17	B	1.53	2.6	0.18	8.3
Věž	potatoes	Haplic Cambisols	silt	11.1	22.6	41.8	50.3	8	B	1.05	1.8	0.12	8.8

(f) Potatoes conventional
(g) Potatoes aerated during vegetation

A rainfall simulator was used to measure the surface runoff rates. A rainfall simulator is a device which has been increasingly used to study soil erosion processes, and the use of simulators is widely accepted (Vahabi & Nikkami 2008; Kovář et al. 2012, etc.). The rainfall simulator has been used a couple of times in the past in several foreign studies to determine runoff curves (Auerswald & Haider 1996; Elhakeem & Papanicolaou 2012). However, we have not encountered a study that would comprehensively evaluate multiple wide-row crops and treatment establishing technologies at the same time. The principle of measuring by a rainfall simulator is based on the water spraying on a clearly defined and experimental plot of 21 m^2. The water spraying mode lasts for 30 min during the first rainfall simulation, then there is a 15-min technological break, after which the second rainfall simulation lasting 15 min follows. The spraying intensity is about 1.0 mm/min. Due to the fact that the rainfall simulator detects the course and volume of the surface runoff, it is possible to determine how much water runs off from the rainfall simulation area during a particular time-span. The subsurface runoff was not included in the calculation due to the relatively small size of the experimental area.

The measurement of the selected crops and technologies was carried out in three developmental stages on growing dates defined in the Prediction Rainfall Erosion Losses from Cropland East of the Rocky Mountains: A Guide for Selection of Practices for Soil and Water Conservation (Wischmeier & Smith 1965).

(I) – date of measurement (second growth period) – period from plot preparation to sowing up to one month after sowing or planting.
(II) – date of measurement (third growth period) – period to the end of second month from the spring or summer sowing.
(III) – date of measurement (fourth growth period) – from the end of the third period up to harvest.

Determination of runoff curve numbers from runoff data and statistical analysis. The basic material for the evaluation of the CN curves numbers from the measured data is the NEH methodology. The first step was to determine the potential maximum retention (S) from the simulated events. Its algebraic calculation is based on the knowledge of the achieved precipitation P and runoff Q on the experimental area. In this approach, the scatter in

https://doi.org/10.17221/114/2020-SWR

the S data is assumed to be described by a log normal distribution around the median. The value of the initial abstraction ratio for most of our measurements ranged from 0.04 to 0.06. For this reason, we decided to use the equation according to Woodward et al. (2003) to calculate the potential maximum retention (S) containing lambda 0.05. Hawkins et al. (2009) identified λ = 0.05 which would be more appropriate to use in runoff calculations for various parts of the world, as this value produced a greater coefficient of determination and a standard error smaller than 0.2.

$$S_{0.05} - 10\,[(2P + 19Q) - \sqrt{361Q^2 + 80PQ}]$$

The next step was to calculate the decimal logarithm of the potential maximum retention for each rainfall-runoff event and to determine its mean and standard deviation. The last step was to calculate the median value of the curve number and its boundary. The following equation adapted to a metric system was used to calculate the median curve number:

$$\text{CN} = \frac{25\,400}{254 + S}$$

The curve numbers for 10% and 90% of the extremes correspond with the 1.282 percentiles of the normal distribution. Descriptive statistics were firstly performed for each dataset. This included the determination of the arithmetic mean, standard deviation and sample size. Each dataset (CN values) was also examined for a normal distribution using the Shapiro-Wilk test with a significance level of α = 0.05. As some datasets showed that the CN values did not have a normal distribution, we decided to demonstrate the difference between the soil-conservation technologies and conventional cultivation using the non-parametric Mann-Whitney U test. The test checks the continuous or ordinal data for a significant difference between two independent groups. Basically, the significance of a difference of the location (value) of the medians of two groups is tested. The level of significance was chosen at 0.05 with the right-tailed variant test.

RESULTS AND DISCUSSION

To calculate the runoff of the row crops, this method distinguishes the technologies according to the orientation method of the crop rows on the slope, the presence of terraces on a plot, the presence of plant residue on the surface or a combination of these conditions. At the same time, the hydrological conditions related to the factors influencing the infiltration and runoff are further specified. These are the density and canopy of the vegetative areas, the amount of the year-round cover, the amount of grass or close-seeded legumes, the percent residue cover on the land surface, and the degree of the surface toughness. In addition to the already mentioned properties, the Antecedent Runoff Conditions (ARC) are also reflected in the resulting CN value. These indicators include the rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth and temperature. ARC is divided into three classes: II for average conditions, I for dry conditions, and III for wetter conditions. In our measurements, the second simulation carried out on wet soil is associated with the ARC III curve, where this connection corresponds to the original classification according to AMC (Antecedent Moisture Condition criteria) and its sum of the total precipitation within the previous 5 days. The first simulation carried out on naturally dry soil then corresponded to the conditions for the ARC II curve for most of the performed simulations.

In our research, we also dealt with and addressed the question of the extent to which the CN values were affected by neglecting the subsurface runoff. We found the answer in the study of Mazur (2018), who, on the soil of a haplic luvisol and a slope of 11% (similar conditions to the locality Jevíčko) derived the ratio between the rainfall and the rate of the subsurface runoff. In our case, it is approximately 1% of the subsurface runoff from the simulated rainfall. Therefore, we believe that the non-inclusion of the subsurface runoff in the calculation did not fundamentally affect the overall resulting value.

Results of CN values for conventional technologies of cultivating row crops. According to the information from NEH, for a row crop with straight rows cultivated on soil with hydrological group B, the values are in the range of 90–92 are stated for ARC III. In our case, in the second simulation carried out on the saturated soil, CN values in the range of 93–94 were found for the monitored row crops. As for ARC II, the methodology states that the CN values are in the range of 78–81. This result would correspond to the set value of 81 in maize. A similar result for the conventional technology of growing maize was obtained by Elhakeem and Papanicolaou (2009), when they determined a CN value of 82 in the Cass locality in the summer. This measurement was also carried out using a rainfall simulator on

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Table 2. Comparison of the curve number (CN) values according to National Engineering Handbook (NEH) with simulated rainfall for conventionally cultivated row crops

Antecedent runoff condition	NEH row crops – straight row hydrologic soil group B hydrologic condition		Moisture condition	Conventional tillage		
	good	poor		maize	hops	potatoes
ARC III	90	92	saturated soil – second simulation	94	94	93
ARC II	78	81	natural moisture – first simulation	81	83	86
ARC I	60	64				

the soil with hydrological group B/D and under moisture conditions corresponding to ARC II. In the conventional technology of hop and potatoes cultivation, however, the resulting values were set slightly higher, i.e., 83 and 86. The results comparison is shown in Table 2. Furthermore, a chart (Figure 2) of the resulting CN values for the first measurement, based on ARC III for the saturated measurement technology, was created. ARC III was chosen because it represents the most uniform conditions, which can be substantiated by the relatively low standard deviations of the second simulation.

Results of CN values for soil conservation technologies of cultivating row crops. The soil conservation technologies of the selected row crops were compared with the technology according to the information from NEH, which considers straight rows down the slope with plant residue on the surface (crop residue cover). The assessment was carried out again on a soil with hydrological group B, where the CN values for ARC III are reported in the range of 88–91. Virtually the same values for the CN curves were found in the assessed crops (Table 3). The lowest values were found for the soil conservation technologies in maize and the highest values were found in potatoes. The first simulation corresponding to the conditions for ARC II had disproportionately lower results for the CN curves for the soil conservation technologies, having some exceptions compared to the methodology (Figure 3). It states that the CN values for ARC II are in the range of 75–80. The measurements showed the lowest value for the strip-tillage technology, where the CN value only reached 56. Another technology significantly below the stated range was the technology for cultivating no-till maize with a value of 67.

In terms of the resulting CN value for maize cultivated by the no-till technology, our results also differ slightly from the study by Elhakeem and Papanicolaou (2009), which states that the summer CN value at the Cass 77 site (hydrological soil group B/D) and at the Pocahontas 75 site (hydrological soil group B and B/C) Slightly lower compared to the NEH methodology was also the technology for cultivating hops with catch crop, where CN reached 72. The only exception was the technology of potatoes aerated during the growing season. Although this technology is generally considered to be a soil conservation method, it had a slightly higher CN value which reached a value of 82. This clearly showed the positive effect of the plant residue or the effect of the whole plants in the interrows, which have a significant role in reducing the

Table 3. Comparison of the curve number (CN) values according to National Engineering Handbook (NEH) with simulated rainfall for the soil conservation technologies cultivated row crops

Antecedent runoff condition	NEH row crops -straight row with crop residue cover hydrologic soil group B hydrologic condition		Moisture condition	Maize strip-tillage	Maize no-tillage	Hops with catch crops	Potatoes aerated during vegetation
	good	poor					
ARC III	88	91	saturated soil – second simulation	88	88	90	92
ARC II	75	80	natural moisture – first simulation	56	67	72	82
ARC I	57	63					

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Table 4. Statistical difference of the resulting curve number (CN) values during the first simulation

Group	Crop and technology	Sample size (n)	Arithmetic mean ($\bar{x}$)	CN median	CN 10 %	CN 90 %	SD	Shapiro-Wilk test *P*-value α = 0.05
1	maize conventional tillage	44	80	81	69	89	7.7	0.088
2	maize strip-tillage	12	56	56	42	70	10.6	0.486
3	maize no-tillage	15	66	67	50	81	12.1	0.323
Mann-Whitney U test one tails right		hypothesis H1		group 1 > group 2			group 1 > group 3	
		Z value		4.86			3.96	
		P-value α = 0.05		5.95E-07			3.68E-05	
1	hops conventional tillage	13	83	83	75	89	5.4	0.934
2	hops with catch crops	18	70	72	53	85	12.3	0.676
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.91			
		P-value α = 0.05			1.83E-03			
1	potatoes conventional tillage	13	86	86	81	91	3.9	0.672
2	potatoes aerated during vegetation	19	82	82	76	87	4.9	0.004
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.18			
		P-value α = 0.05			0.01			

SD – standard deviation

surface runoff within the lower soil saturation. Cover crops on the soil surface can have different efficiency which depends on the cover quality and degree of their decomposition. The cover crops' quality in soil conservation technologies changes throughout the years. Thus, the standard deviation of the CN values is higher in soil conservation technologies with cover crops than the standard deviation of the CN values in technologies without cover crops (all conventional technologies and the technology of potatoes aerated during vegetation).

Statistical difference between the measured CN values conventional and soil conservation technologies. A significant statistical difference was proven between the measured CN values and the conventional and soil conservation technologies in all the evaluated

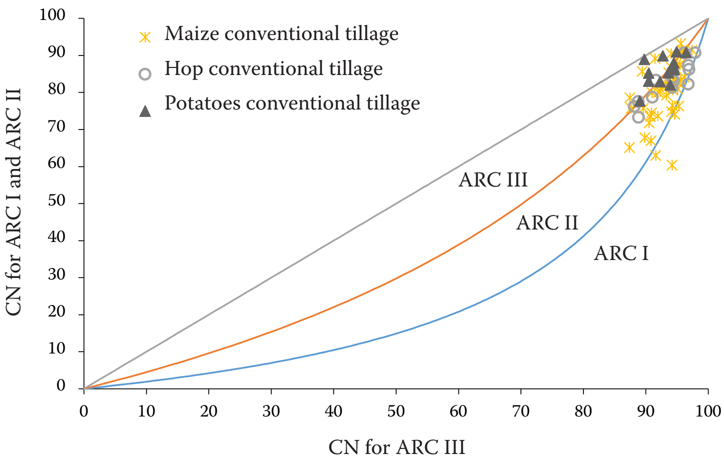

Figure 2. Curve number (CN) values corresponding to the first simulation according to the ARC III curve for the conventional technologies of cultivating row crops

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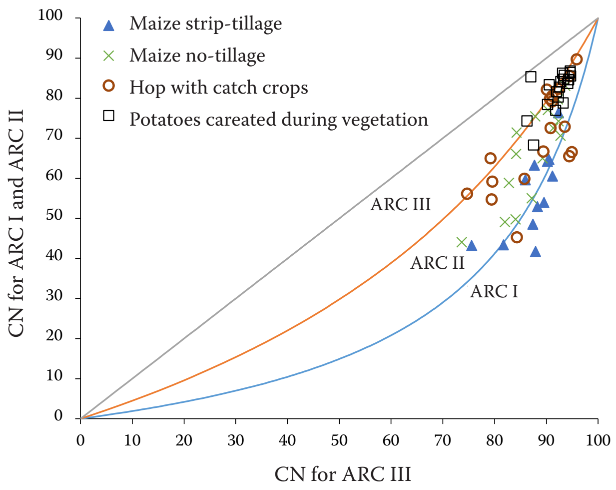

Figure 3. Curve number (CN) values corresponding to the first simulation according to the ARC III curve for the soil conservation technologies of cultivating row crops

crops during the first simulation (Table 4). The lowest *P*-values were achieved in both soil conservation technologies of cultivating maize; however, very good results were also achieved in hops with a catch crop. In the case of the technology of potatoes aerated during vegetation, the *P*-value was found to be the highest of all the assessed soil conservation technologies. Nevertheless, at a significance level of α = 0.05, it was still demonstrably statistically different from the CN value for the conventional technology. In the case of the second simulation, a significant statistical difference was proven between the technologies in the soil conservation technologies of cultivating maize and hops (Table 5). Likewise, the first simulation, the lowest *P*-values were determined for maize with the strip-till and no-till technologies. A slightly higher *P*-value was then found in the technology of hops with a catch crop. However, at a significance level of α = 0.05, this technology is still significantly different from the conventional one. In the last assessed technology for potatoes, it was not possible to reject the hypothesis of conformity of the assessed files of the resulting CN values, where the *P*-value value only reached 0.16. Thus, the technology of potatoes aerated during the growing season was not statistically different from the conventional method of cultivating potatoes.

Table 5. Statistical difference of the resulting curve number (CN) values during the second simulation

Group	Crop and technology	Sample size (n)	Arithmetic mean ($\bar{x}$)	CN median ($\tilde{x}$)	CN 10 %	CN 90 %	SD	Shapiro-Wilk test *P*-value α = 0.05
1	maize conventional tillage	44	93	94	90	96	2.5	0.004
2	maize strip-tillage	12	87	88	82	92	4.4	0.017
3	maize no-tillage	15	87	88	80	93	5.4	0.207
Mann-Whitney U test one tails right		hypothesis H1		group 1 > group 2			group 1 > group 3	
		Z value		4.38			4.19	
		P-value α = 0.05		5.95E-06			1.37E-05	
1	hops conventional tillage	13	94	94	88	97	3.5	0.180
2	hops with catch crops	18	88	90	80	95	6.4	0.030
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.23			
		P-value α = 0.05			0.01			
1	potatoes conventional tillage	13	93	93	90	96	2.4	0.053
2	potatoes aerated during vegetation	19	92	92	89	95	2.6	0.011
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			1.01			
		P-value α = 0.05			0.16			

SD – standard deviation

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CONCLUSION

As the results of the CN values show, the conventional row crop technology reported in the NEH methodology for ARC II and III was only slightly lower compared to the values found in this study, however, it generally coincides with them. In the case of the soil conservation technologies, the achieved CN values for the second simulation were practically the same as in the methodology corresponding to ARC III. A disproportionately larger difference was found in the first simulation, in which the achieved values for the soil conservation technologies were closer to the values of ARC I. In this respect, there was only one exception for the technology of aerated potatoes during vegetation, with the CN value corresponding more to ARC II. However, the reason for this is the fact that this soil conservation technology is based only on regular aeration without any additional soil cover outside the main crop. Based on our findings, we can state that the NEH methodology and the reported CN values correspond relatively well to the hydrologic soil group B in the Czech Republic. Only for some soil conservation technologies, which NEH does not distinguish for the time being, the CN values can, under certain conditions, be higher than stated.

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4.7 Půdoochranné technologie ve vztahu k organické hmotě

V případě trvale udržitelného hospodaření se často mluví o organické hmotě. Na zemědělských půdách bývá obsah organické hmoty v půdě malý (jednotky procent), přesto představuje jeden z nejdůležitějších faktorů ovlivňující její úrodnost, strukturu, celkovou stabilitu aj. Organická hmota je tvořena živými půdními organismy a jejich zbytky v různém stupni rozkladu či přeměny.

Je obecně známo, že půdy s dostatečným obsahem organické hmoty jsou odolnější vůči zhutnění, lépe zadržují vodu, mají vyšší sorpční schopnost a vykazují vyšší produkční potenciál. Naopak její nadměrný úbytek je označován za degradační proces, jehož výsledkem je snížení úrodnosti a zvýšená náchylnost k výskytu dalších degradačních procesů (včetně vodní eroze). Níže uvedené odborné publikace jsou zaměřeny na problematiku organické hmoty v půdě.

Většina silně protierozně účinných půdoochranných technologií je založena na rostlinných zbytcích na povrchu půdy či na využití pomocných plodin. V důsledku takového agrotechnického postupu hospodaření dochází ke zvýšenému přísunu organické hmoty do půdy ve srovnání s konvenčními technologiemi. S tím souvisí následné riziko jejího vyplavování (viz **Publikace 3**). Z tohoto důvodu byla snaha problematiku dále vědecky prohloubit. **Publikace 12** je zaměřena na vyplavování organické hmoty z půdy působením vodní eroze ve vztahu k zrnitostním frakcím půdy a sklonitosti pozemku.

Při hodnocení půdní organické hmoty je možné její obsah vyjadřovat pomocí různých parametrů. Mezi tyto parametry patří: celkový uhlík (TC – total carbon), celkový organický uhlík (TOC – total organic carbon), celkový anorganický uhlík (TIC – total inorganic carbon), oxidovatelný uhlík (C_{ox} – oxidizable carbon), labilní uhlík (labile carbon), stabilní uhlík (stable carbon), uhlík mikrobiální biomasy (MBC – microbial biomass carbon), uhlík mikrobiální bazální respirace (MBR – microbial basal respiration), apod. Problematikou některých těchto forem ve vztahu k udržitelnému managementu hospodaření se zabývá **Publikace 13**. **Publikace 14** pak řeší aktivitu mikrobiální části (MBC, MBR) organické hmoty v závislosti na půdní reakci (výši pH), jakožto klíčové složky půdy podílející se na rozkladu primární organické hmoty.

Publikace 12

Název

Preferential Erosion of Soil Organic Carbon and Fine-Grained Soil Particles - An Analysis of 82 Rainfall Simulations.

Citace

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Article

Preferential Erosion of Soil Organic Carbon and Fine-Grained Soil Particles—An Analysis of 82 Rainfall Simulations

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Abstract: Soil erosion by water causes the loss of soil mineral particles and soil organic carbon (SOC). For determining the effectiveness of soil conservation measures on arable land, rainfall simulations are regularly carried out in field trials in the Czech Republic. The objective of this study was to analyse a dataset from 82 rainfall simulations on bare fallow soils, containing information on slope inclination, soil texture, soil bulk density, SOC, and soil loss with respect to the preferential erosion of fine-grained soil particles and the enrichment of SOC in the eroded soil. Each rainfall simulation comprised a first rainfall period of 30 min and a second one of 15 min in duration. The rainfall intensity was 1 mm min^{-1} and the kinetic energy of the raindrops accounted for 8.78 J m^{-2} mm^{-1}. Runoff samples were taken to determine the soil loss and SOC enrichment in the eroded material. Regression analyses revealed that on sites with <14% slope inclination, SOC mitigated soil loss in the first rainfall period. On sites with >14% slope inclination, soil loss was driven by preferential erosion of fine-grained particles in the first rainfall period. Low soil loss was generally coupled with high SOC enrichment and vice versa, indicating that preferential erosion of SOC occurred mainly in soils with low erosion susceptibility. In order to prevent erosion of SOC and maintain soil quality, soil conservation measures are important in all soil types.

Keywords: soil organic carbon; soil erosion; preferential erosion; enrichment ratio; rainfall simulation

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1. Introduction

Soil organic carbon (SOC) plays an important role in food security and climate change mitigation by means of carbon sequestration [1]. Moreover, SOC is a key parameter for the physical, chemical, and biological quality of soils [2]. Organic matter acts as a binding agent in the formation of soil aggregates, which in turn protect the associated SOC from decomposition [3,4]. Soil organic carbon stabilises soil aggregates against rainfall-induced disruption [5] and increased SOC content reduces soil erosion [6–8].

Conversely, soil erosion causes a loss of SOC, as both mineral particles and organic matter are exported from their original site. Soil erosion is a selective process with respect to both particle size distribution and SOC content; fine soil particles and organic matter are enriched in the eroded material as compared to the source material [7,9–11]. This means that clay, silt, and SOC are preferentially relocated by soil erosion. This comparable behaviour of fine soil particles and SOC is not random, as SOC content and the amount of fine-grained particles of <63 μm size are positively correlated [7]. It was also found that

86% to 91% of the SOC is associated with soil mineral particles [10] and that 77% of the SOC in cropland soils is stored in the fraction of particles < 20 µm [12]. The enrichment ratio (ER) is a measure for the selective erosional process, where ER > 1 indicates an enrichment and ER < 1 indicates a depletion in the eroded material in relation to the source material [7]. Rainfall simulations revealed for soil particles of <20 µm size an ER in between 1.5 and 2.0, for particles from 20 µm to 63 µm size an ER of approximately 1.0, and for particles of >63 µm size an ER of approximately 0.5 [7]. The organic fractions of <63 µm size had an ER in between 1.5 and 2.0 and the organic fractions of >63 µm size had an ER of in between 1.0 and 1.2 [7]. In another experiment, the carbon ER of eroded sediments was found to range between 1.3 and 4.0 [10] and a meta-analysis revealed an average carbon ER of 1.5 for eroded sediments [13].

Soil erosion is predominantly an issue on agricultural land, where soil loss is about 40 times higher than on forestland and about 20 times higher than on other semi-natural vegetation areas [14]. The estimated average soil loss rate due to erosion by water is 3.6 Mg ha^{-1} yr^{-1} for arable land in the EU [15] and 4.2 Mg ha^{-1} yr^{-1} for agricultural land on a global average, respectively [16]. Estimates of SOC loss due to soil erosion by water showed a global average rate of 193 kg ha^{-1} yr^{-1} for cropland [16] and an EU average rate of 68 kg ha^{-1} yr^{-1} for agricultural land [17]. The reasons for the increased erosion susceptibility of agricultural soils in comparison to forestland soils and semi-naturally vegetated soils are the high quantity and intensity of cultivation activities. Therefore, the soil is mechanically disturbed and often not or only sparsely covered by vegetation and plant litter, exposing it to a high risk of soil erosion. Although some approaches such as reduced tillage, no-tillage, organic farming and cover crop cultivation have been proven to effectively mitigate soil erosion [6,18,19], they tend to have an increased risk of reduced yields [20–22]. Therefore, the adoption of such erosion-mitigating technologies is currently limited and soil erosion on arable land still remains a serious issue, leading additionally to decreases in crop yields [23–25].

Rainfall simulations in the field are a method to experimentally determine organic matter loss due to soil erosion by water [7,26]. In the Czech Republic, rainfall simulations are regularly carried out in different field trials throughout the country [26–30]. A frequent aim of these rainfall simulations is the evaluation of the erosion-mitigating potential of different crop management approaches established on the experimental plots, e.g., cover crop and catch crop cultivation, strip-tillage and no-tillage [26–29]. From such measurements, a comprehensive dataset exists. To date, these data have not been analysed regarding the preferential erosion and enrichment of fine-grained soil particles and SOC. However, such information could provide a useful basis for assessing sediment and SOC dynamics in terms of soil erosion. Preferential erosion and enrichment have an influence on sediment and organic carbon transport processes throughout the landscape. Likewise, they influence the ability to trace sediments and organic carbon in the landscape back to their sites of origin. So-called fingerprinting techniques use a variety of physical and biochemical parameters, i.e., fingerprints, for discriminating between sediment sources [31]. Such parameters are often corrected for differences in particles size distribution and organic carbon content between the source soil and the eroded sediment [32,33]. In order to assess the validity of correction factors, however, a better understanding of erosional processes and more attention to the enrichment and depletion effects of fine particles and SOC are needed [32,33]. The present article has the potential to contribute to the comprehension and consideration of such processes. Moreover, it is aimed at providing a basis for deducing appropriate soil conservation measures on arable land.

The objective of this study was to analyse a dataset from the Czech Republic with respect to both the preferential erosion of fine-grained soil particles and the enrichment of SOC in the eroded material. The research questions were as follows: How do soil texture and SOC content influence the soil loss rate? Is the eroded material enriched in SOC as compared to the source material and if it does so, what influence on the enrichment do the soil loss rate, soil texture, and SOC content have?

In order to exclude vegetation impacts with varying influences on erosional processes, only plots with bare fallow treatment were considered. This approach also allowed for emulating the still widespread practice of leaving the soil uncovered for a certain amount of time throughout the year, thereby exposing it to a high risk of soil erosion.

2. Materials and Methods

2.1. Sites and Rainfall Simulation

From 2014 to 2020, rainfall simulations were carried out from May to September on 19 inclined sites in the Czech Republic. The geographical location of the sites is presented in Figure 1. For each site, the GPS location, total of rainfall simulations, slope gradient, particles size distribution, texture class, SOC content, and soil bulk density are given in Table 1. In order to exclude vegetation impacts and to emulate the practice of leaving the soil uncovered for a certain amount of time, only rainfall simulations carried out on vegetation-free bare fallow were considered in this study. A total of 82 rainfall simulations was analysed.

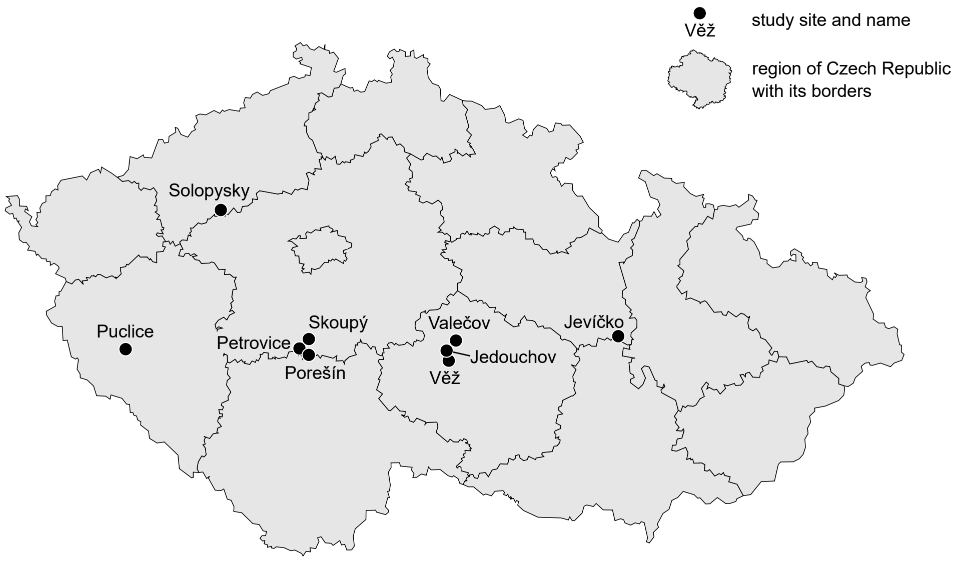

Figure 1. Location of the study sites within the Czech Republic. Note: This map is a modified version of the blank vector map provided by mapsvg.com [34], which is distributed under the terms and conditions of the Creative Commons Attribution 4.0 International (CC BY 4.0) license [35].

Table 1. Site and soil characteristics of each rainfall simulation site: GPS location, total of rainfall simulations from 2014 to 2020, slope gradient, mean clay (<2 µm) content, mean silt (2 µm to 50 µm) content, mean sand (50 µm to 2000 µm) content, soil texture class according to [36], mean soil organic carbon (SOC) content, and mean soil bulk density.

Site	GPS Location	Total of Rainfall Simul.	Slope Gradient	Clay Content	Silt Content	Sand Content	Texture Class	SOC Content	Bulk Density
			(%)	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})		(g kg^{-1})	(g cm^{-3})
Jedouchov	49.5795028N, 15.4489581E	3	12.5	86	274	640	SL	13.0	1.65
Jevíčko 1	49.6257850N, 16.7212519E	1	11.8	257	490	253	L	10.3	(n.d.) [3]
Jevíčko 2	49.6560531N, 16.7088942E	10	9.3	234	533	234	SiL	13.0	1.53
Jevíčko 3	49.6239792N, 16.7285842E	3	9.4	257	684	59	SiL	18.6	1.31

Table 1. *Cont.*

Site	GPS Location	Total of Rainfall Simul.	Slope Gradient (%)	Clay Content (g kg^{-1})	Silt Content (g kg^{-1})	Sand Content (g kg^{-1})	Texture Class	SOC Content (g kg^{-1})	Bulk Density (g cm^{-3})
Petrovice 1	49.5684642N, 14.3257247E	4	13.3	181	273	546	SL	10.5	1.55
Petrovice 2	49.5523536N, 14.3295014E	8	11.7	73	254	674	SL	10.7	1.44
Petrovice 3	49.5617119N, 14.3204194E	3	9.1	75	214	711	SL	8.1	1.45
Porešín	49.5379558N, 14.3668522E	3	15.1	43	255	702	SL	10.7	1.41
Puclice	49.5864069N, 13.0128503E	7	11.5	97	460	444	L	15.5	1.44
Skoupý 1	49.5798861N, 14.3581947E	3	12.4	61	365	574	SL	13.8	1.25
Skoupý 2	49.5803894N, 14.3593669E	3	13.4	61	365	574	SL	15.5	1.42
Skoupý 3	49.5763589N, 14.3567811E	2	15.6	85	186	729	SL	9.4	1.57
Solopysky 1	50.2591408N, 13.7416328E	13	17.0	256	444	300	L, CL [1]	14.2	1.49
Solopysky 2	50.2562844N, 13.7345892E	5	9.0	278	432	290	L, CL [2]	10.7	1.38
Valečov	49.6388550N, 15.4891042E	3	9.6	110	235	655	SL	9.7	1.39
Věž 1	49.5644553N, 15.4517247E	3	8.6	129	296	575	SL	9.5	1.41
Věž 2	49.5751233N, 15.4700092E	3	10.7	96	322	582	SL	12.1	1.28
Věž 3	49.5545625N, 15.4507564E	2	10.2	99	389	512	L	10.7	1.20
Věž 4	49.5629433N, 15.4496219E	3	9.4	101	410	489	L	12.8	1.42

Texture class abbreviations: CL—clay loam; L—loam; SiL—silt loam; SL—sandy loam. [1] For the Solopysky 1 site, the average clay, silt, and sand contents are in accordance with a loam texture. However, 3 out of the 13 samples had a clay loam texture. [2] For the Solopysky 2 site, the average clay, silt, and sand contents are in accordance with a clay loam texture. However, three out of the five samples had a loam texture. [3] (n.d.)—no data.

The rainfall simulator (Figure 2) had four sprinklers with an adjusted water pressure of 50 kPa. The rainfall intensity was set to about 1 mm min^{-1}, which corresponds to the average heavy rainfall intensity in the Czech Republic [37]. The average raindrop diameter accounted for 1.5 mm to 2.0 mm and the average kinetic energy of the raindrops accounted for 8.78 J m^{-2} mm^{-1}. The sprinklers were installed 2 m above the soil surface and an area of 21 m^2 (9.0 m × 2.33 m) was irrigated (Figure 2). The long sides of this area were placed parallel to the runoff direction. In order to prevent lateral runoff, steel sheets bordered the long sides. On the bottom side, the surface runoff was concentrated by means of a flume (Figure 2). A tipping bucket runoff gauge was placed downstream of the flume outlet (Figure 2). The counts of the gauge were recorded by a computer, which allowed for the continuous measurement of surface runoff.

Before each rainfall simulation, the soil was shallowly cultivated and subsequently levelled with a water-filled roller. Each rainfall simulation comprised two rainfall periods. The first rainfall had a duration of 30 min and was carried out at the present soil moisture content in order to simulate a heavy rainfall event on unsaturated soil. After a 15 min break, the second rainfall with a duration of 15 min was performed on the beforehand-irrigated soil in order to simulate a heavy rainfall event on the nearly saturated soil. The break in between both rainfall periods allowed for ponded water for infiltrating or running off until the start of the second period. For practical reasons, the rainfall simulator was fed with process water used on the farms to which the sites belong, e.g., groundwater or rainwater.

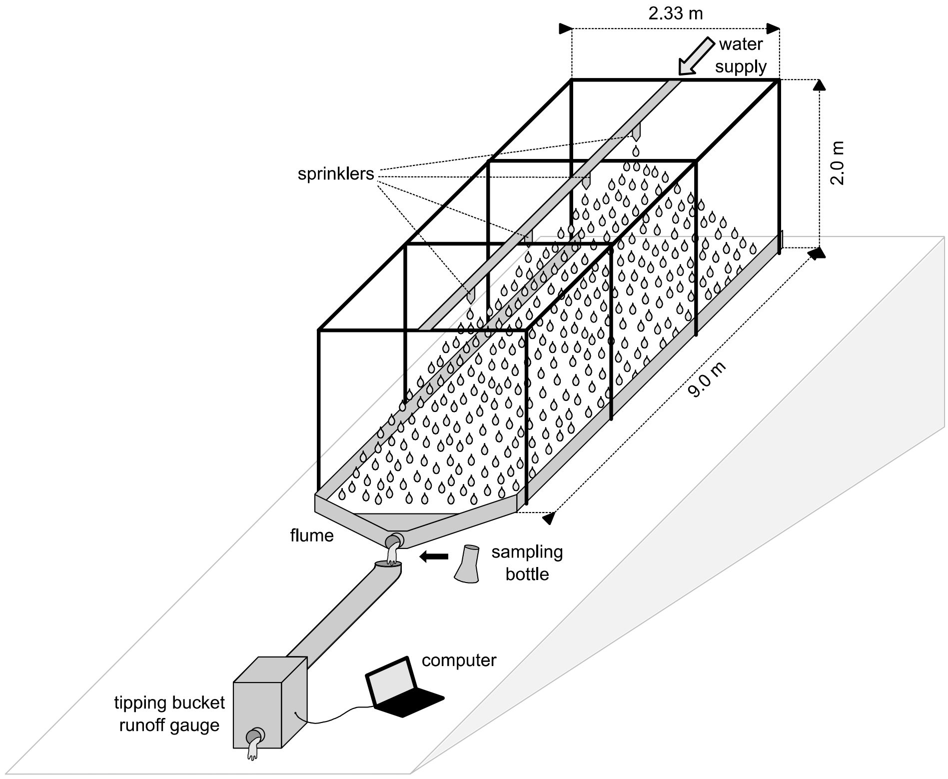

Figure 2. Scheme of the rainfall simulator and the equipment setup.

2.2. Sampling, Laboratory Analyses, and Calculations

After the surface runoff flow reached the outlet of the flume, runoff samples for collecting the eroded material were taken every three minutes into a sampling bottle with a volume of 319 mL until full (Figure 2). Each runoff sample was decanted into a plastic bottle for transport and stored at room temperature until the analyses. Disturbed soil samples were taken by means of a garden trowel at three points 0.5 m uphill of the irrigation area from 0 cm to 5 cm soil depth, mixed to one bulked sample, and stored in plastic bottles at room temperature until the analyses. Before the start of the rainfall simulation, undisturbed soil core samples (100 cm^3 volume) were collected within the irrigation area 0.5 m downhill of its upper boundary from 0 cm to 5 cm soil depth, transported in cooling boxes, and stored in a refrigerator until the analyses.

The runoff samples were dewatered by means of evaporation. The organic carbon content of the source soil (from the disturbed soil samples) and eroded soil (from the runoff samples) was determined by means of sulfochromic oxidation [38]. All of the samples were dried for 12 h at 105 °C in an oven. The particle size distribution of the source soil (from the disturbed soil samples) was analysed by means of sieving and sedimentation [39], and the following texture size classes were determined: clay (<2 µm), silt (2 µm to 50 µm), and sand (50 µm to 2000 µm). Soil bulk density was determined from the undisturbed samples by means of the core method [40]. The weight of the dried eroded sediment (from the runoff samples) was gravimetrically measured.

As runoff samples were taken every three minutes, the sediment concentration in the runoff was calculated in 3 min steps at k times according to:

$$c_i = \frac{m_i}{RO_i};\ i = 1,\ 2,\ \ldots,\ k, \tag{1}$$

where c_i is the sediment concentration in the runoff at time i, m_i is the mass of the eroded sediment at time i, and RO_i is the surface runoff at time i. Each sediment concentration in the runoff c_i was set constant for three minutes, i.e., until the next runoff sampling time. Runoff data were recorded in 1 s steps for n time intervals and the soil loss for each time interval j was calculated according to:

$$m_j = c_i\ RO_j;\ i = 1,\ 2,\ \ldots,\ k;\ j = 1,\ 2,\ \ldots,\ n;\ k < n, \tag{2}$$

where m_j is the mass of the eroded sediment for the jth time interval and RO_j is the surface runoff for the jth time interval. The soil loss rate of each rainfall period was calculated according to:

$$\text{soil loss rate} = \frac{\sum_{j=1}^{n} m_j}{A\ t}, \tag{3}$$

where A is the irrigated area, i.e., 21 m^2, and t is the duration of rainfall, i.e., 30 min for the first period and 15 min for the second period.

The enrichment ratio of soil organic carbon (ER_{SOC}) was calculated according to:

$$ER_{SOC} = \frac{SOC_{eroded}}{SOC_{source}}, \tag{4}$$

where SOC_{eroded} is the soil organic carbon content in the eroded material and SOC_{source} is the soil organic carbon content in the source soil. Since the ER_{SOC} of the second rainfall period showed a range of remarkably high values (Sections 3.2 and 4.2), these data have been subjected to an outlier detection by means of Tukey's fences (k = 1.5). Values with ER_{SOC} > 3.14 were recognised as outliers and excluded from the subsequent regression analyses.

2.3. Statistical Analyses

Simple linear regression was carried out for modelling the relationships between soil texture, SOC content, soil loss rate, and ER_{SOC}. The SOC content in the source soil was fitted against clay (<2 µm) content, silt (2 µm to 50 µm) content, and clay + silt (<50 µm) content; soil loss rate was fitted against clay content, silt content, clay + silt content, and SOC content; and ER_{SOC} was fitted against clay content, silt content, clay + silt content, SOC content, and soil loss rate. To account for the influence of slope steepness on the SOC content, the data were divided into two groups: one with sites with a slope inclination < 14% and one with sites with a slope inclination > 14%, respectively. Simple linear regressions were carried for each of these groups separately. The same procedure was applied for the regressions including ER_{SOC}. However, the group of sites with a slope inclination > 14% comprised only eight scattered values, and this was considered as insufficient for drawing a reliable conclusion. Therefore, the regressions for ER_{SOC} are presented for all of the sites together without differentiating according to slope steepness.

Each model was tested for normally distributed residuals by means of the Shapiro–Wilk test. Whenever a linear model did not have normally distributed model residuals, a generalised linear model assuming a Gamma distribution was applied instead. The Gamma distribution was assumed, since the data tended to be right-skewed in these cases. For each parameter fitting combination carried out in the simple linear regression, the Pearson product–moment correlation coefficient (r) was calculated.

All of the statistical analyses were carried out by means of the software R, version 4.1.0 (The R Foundation for Statistical Computing, Wien, Austria). The same applied for the creation of the graphs.

3. Results

3.1. SOC Content in the Eroded Soil and the Soil Loss Rate

The soil organic carbon content in the eroded material had a higher mean and a higher variation in the second rainfall period as compared to the first one (Table 2). The soil loss rate in the second rainfall period was lower than in the first one (Table 2).

3.2. Enrichment Ratio of SOC

On average, there was an enrichment of SOC in the mobilised soil as compared to the source soil (Table 2). In the first rainfall period, 68% of the rainfall simulations resulted in an $ER_{SOC} > 1$ and 32% in an $ER_{SOC} < 1$ (Table S1). In the second rainfall period, 67% of the rainfall simulations resulted in an $ER_{SOC} > 1$, 1% in an $ER_{SOC} = 1$, and 32% in an $ER_{SOC} < 1$ (Table S1).

Table 2. Mean values for each site and summary statistics across all of the sites for the soil organic carbon (SOC) content in the eroded soil, for the soil loss rate, and for the soil organic carbon enrichment ratio (ER_{SOC}), determined in 82 rainfall simulations. The first rainfall period (1st) lasted 30 min and the second rainfall period (2nd) lasted 15 min. For ER_{SOC}, the column '2nd ($ER_{SOC} < 3.14$)' contains the mean values and summary statistics of ER_{SOC} in the second rainfall period after removing the data of those 17 rainfall simulations, which resulted in a noticeably high SOC enrichment of $ER_{SOC} > 3.14$ (see Sections 3.2 and 4.2).

Site	SOC Content in Eroded Soil (g kg^{-1})		Soil Loss Rate (g m^{-2} min^{-1})		ER_{SOC} (g kg^{-1}/g kg^{-1})		
	Rainfall Period		Rainfall Period		Rainfall Period		
	1st	2nd	1st	2nd	1st	2nd	2nd ($ER_{SOC} < 3.14$)
Jedouchov	19.3	14.4	14.5	23.6	1.47	1.10	1.10
Jevíčko 1	11.4	10.8	9.9	24.7	1.11	1.05	1.05
Jevíčko 2	12.9	12.3	31.9	46.5	1.00	0.95	0.95
Jevíčko 3	20.4	36.8	22.2	13.1	1.10	1.99	1.99
Petrovice 1	11.9	10.3	25.8	35.2	1.14	1.01	1.01
Petrovice 2	15.2	9.6	26.1	22.3	1.48	0.92	0.92
Petrovice 3	14.6	9.7	19.6	24.6	1.82	1.19	1.19
Porešín	10.0	8.9	37.8	33.1	0.94	0.85	0.85
Puclice	25.4	22.5	12.1	11.1	1.64	1.46	1.46
Skoupý 1	25.8	20.4	8.1	7.3	1.91	1.49	1.49
Skoupý 2	25.5	23.9	2.5	4.4	1.66	1.55	1.55
Skoupý 3	11.8	9.1	22.3	19.1	1.17	0.88	0.88
Solopysky 1	12.3	65.5	61.6	20.6	0.88	4.62	0.63
Solopysky 2	14.1	37.9	19.0	8.3	1.33	3.54	1.69
Valečov	13.4	7.9	24.3	20.1	1.37	0.82	0.82
Věž 1	8.6	7.6	17.2	19.6	0.91	0.78	0.78
Věž 2	17.0	13.9	15.0	16.7	1.44	1.17	1.17
Věž 3	13.3	84.9	43.8	7.4	1.25	8.11	(n.a.) [1]
Věž 4	12.8	52.6	40.7	7.4	0.99	4.22	2.46
median	13.7	13.6	21.1	14.5	1.16	1.28	1.09
mean	15.5	27.2	28.8	21.5	1.25	2.11	1.15
std. error	0.6	3.1	2.6	2.2	0.05	0.23	0.06
min	4.6	2.4	1.0	2.7	0.58	0.30	0.30
max	29.0	131.4	111.7	118.8	2.35	9.48	2.80
n	82	82	82	82	82	82	65

[1] (n.a.)—not applicable, i.e., at the Věž 3 site, the ER_{SOC} in the second rainfall period was > 3.14 in all cases.

The second rainfall period showed a remarkably higher variation in ER_{SOC} than the first period (Table 2) and 24% of the values exceeded the maximum of the first period (Table S1). The maximum of the second period was about four times higher than the one of the first period (Table 2). These observations were related to a range of considerably high SOC contents of in between 40.5 g kg^{-1} and 131.4 g kg^{-1} in the eroded material (Table S1). Such high organic carbon contents in the eroded soil were unlikely to be representing typical SOC contents, since the SOC content of the source soil accounted for 6.3 g kg^{-1} to 19.9 g kg^{-1} (Table S1). It was rather supposed that in some rainfall simulations a high quantity of pure organic matter particles was washed out, affecting the measurement of SOC content (Section 4.2). Therefore, Tukey's fences method was carried out and values of $ER_{SOC} > 3.14$ have been detected as outliers, and this applied to 17 out of 82 rainfall simulations. After removing the data of these 17 rainfall simulations with an $ER_{SOC} > 3.14$ for further statistical analyses, the ER_{SOC} of the second rainfall period had a similar variation and a similar range like the ER_{SOC} of the first period (Table 2).

3.3. Correlations

The soil organic carbon content of the source soil had positive correlations with the silt content, clay + silt content, and to a lesser extent with the clay content (Figure 3).

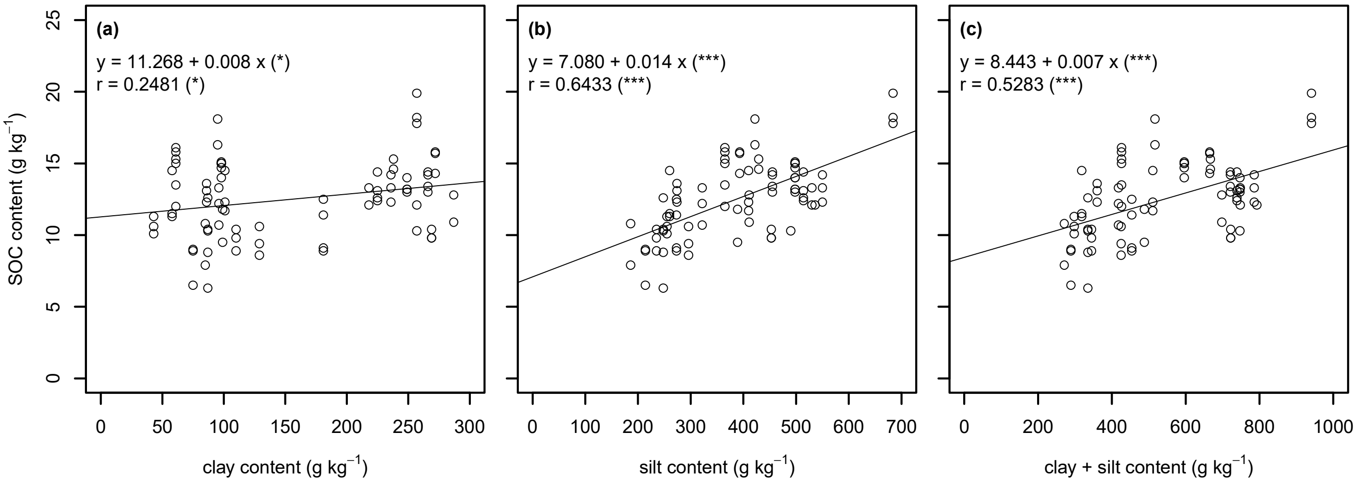

Figure 3. Simple linear regression of soil organic carbon (SOC) content against (**a**) clay content, (**b**) silt content, and (**c**) clay + silt content. The regression functions and Pearson product–moment correlation coefficients (r) are given for each parameter fitting. The significance levels of the regression function slopes and r, indicating a difference from zero, are as follows: (***) $p < 0.001$; (*) $p < 0.05$.

For sites with a slope inclination < 14%, the soil loss correlated negatively with the SOC content in the first rainfall period (Figure 4c) and positively with the clay content in the second rainfall period (Figure 5). For sites with a slope inclination > 14%, the soil loss correlated positively with the silt content, clay + silt content, and SOC content in the first rainfall period (Figure 4).

For the first rainfall period, the ER_{SOC} had negative correlations with the soil loss rate, clay content, clay + silt content, and silt content (Figure 6). For the second rainfall period, the ER_{SOC} showed a negative correlation with the soil loss rate and positive correlations with the SOC content, silt content, and to a lesser extent with the clay + silt content (Figure 7).

Generally, the correlations were not strong as indicated by relatively low Pearson product–moment correlation coefficients r, ranging between 0.2354 (ER_{SOC} vs. clay + silt content, Figure 7b) and 0.6433 (SOC content vs. silt content, Figure 3b) for the significant correlations (Table S2).

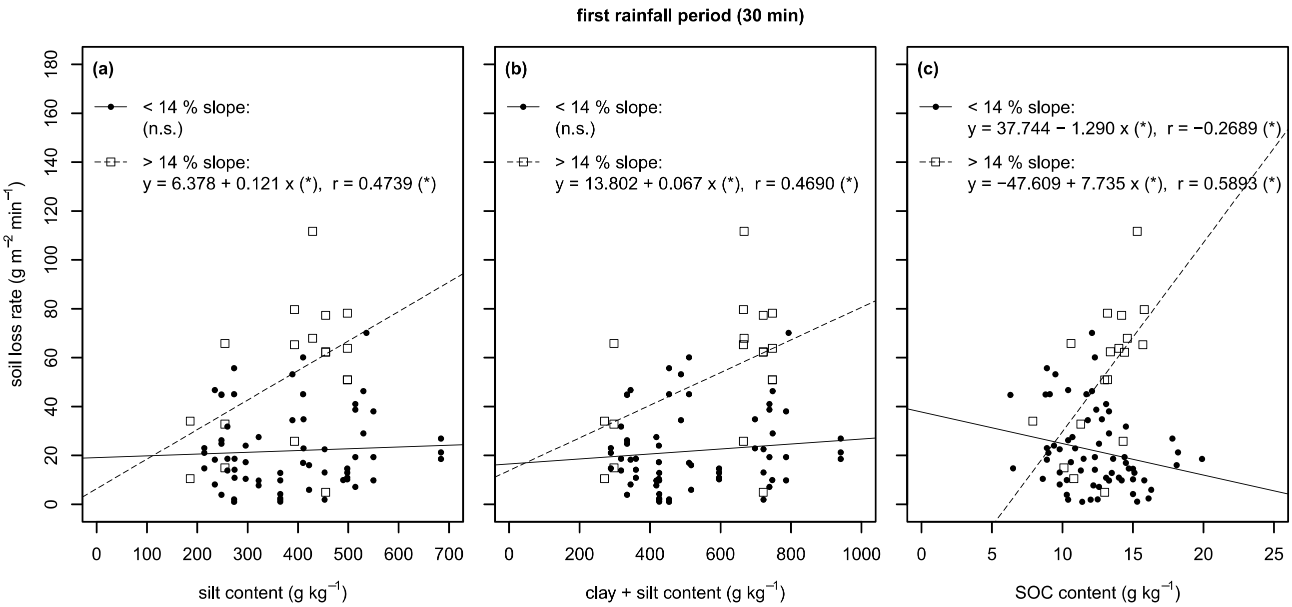

Figure 4. Simple linear regression of the soil loss rate in the first rainfall period (30 min) against (**a**) the silt content, (**b**) clay + silt content, and (**c**) soil organic carbon (SOC) content. For the parameter fittings of sites with < 14% slope inclination, generalised linear models assuming a Gamma distribution have been applied. The regression functions and Pearson product–moment correlation coefficients (r) are given for the significant parameter fittings. The significance levels of the regression function slopes and r, indicating a difference from zero, are as follows: (*) $p < 0.05$; (n.s.) not significantly different at $p < 0.05$.

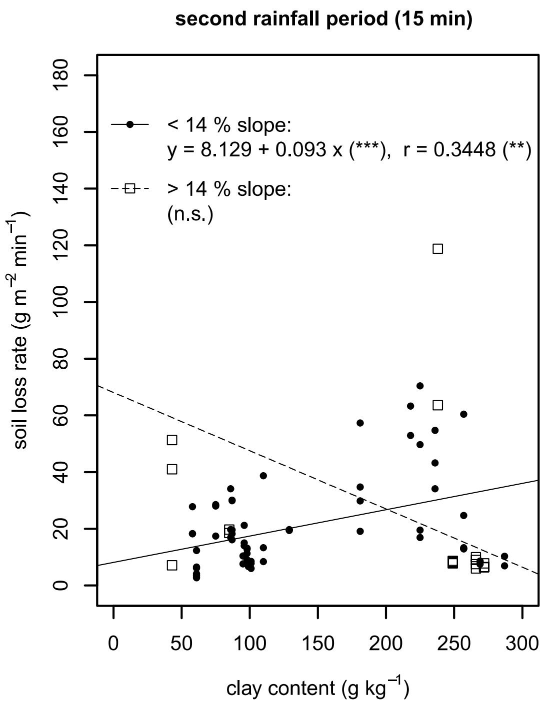

Figure 5. Simple linear regression of the soil loss rate in the second rainfall period (15 min) against the clay content. For each parameter fitting, generalised linear models assuming a Gamma distribution have been applied. The regression function and Pearson product–moment correlation coefficient (r) are given for the significant parameter fitting. The significance levels of the regression function slope and r, indicating a difference from zero, are as follows: (***) $p < 0.001$; (**) $p < 0.01$; (n.s.) not significantly different at $p < 0.05$.

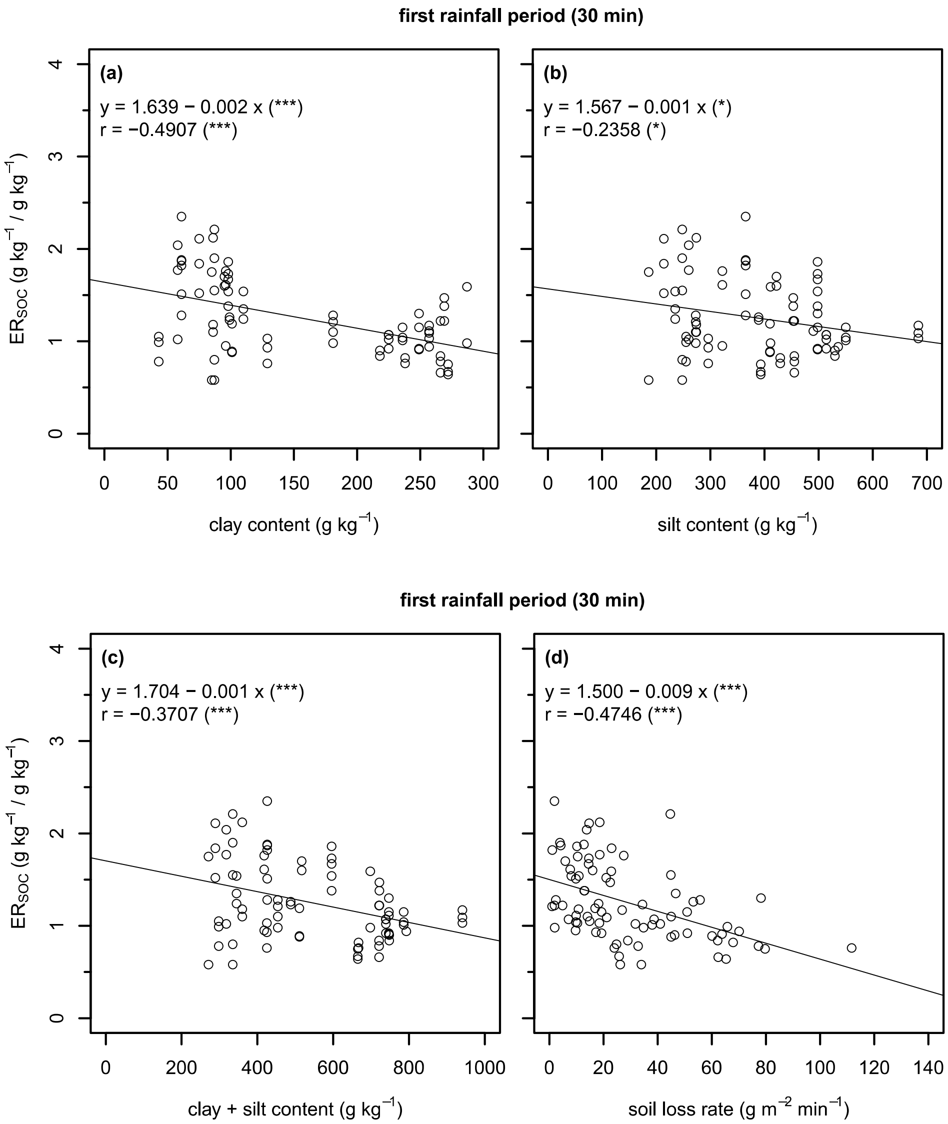

Figure 6. Simple linear regression of the soil organic carbon enrichment ratio (ER_{SOC}) in the first rainfall period (30 min) against (**a**) the clay content, (**b**) silt content, (**c**) clay + silt content, and (**d**) soil loss rate. The regression functions and Pearson product–moment correlation coefficients (*r*) are given for each parameter fitting. The significance levels of the regression function slopes and *r*, indicating a difference from zero, are as follows: (***) $p < 0.001$; (*) $p < 0.05$.

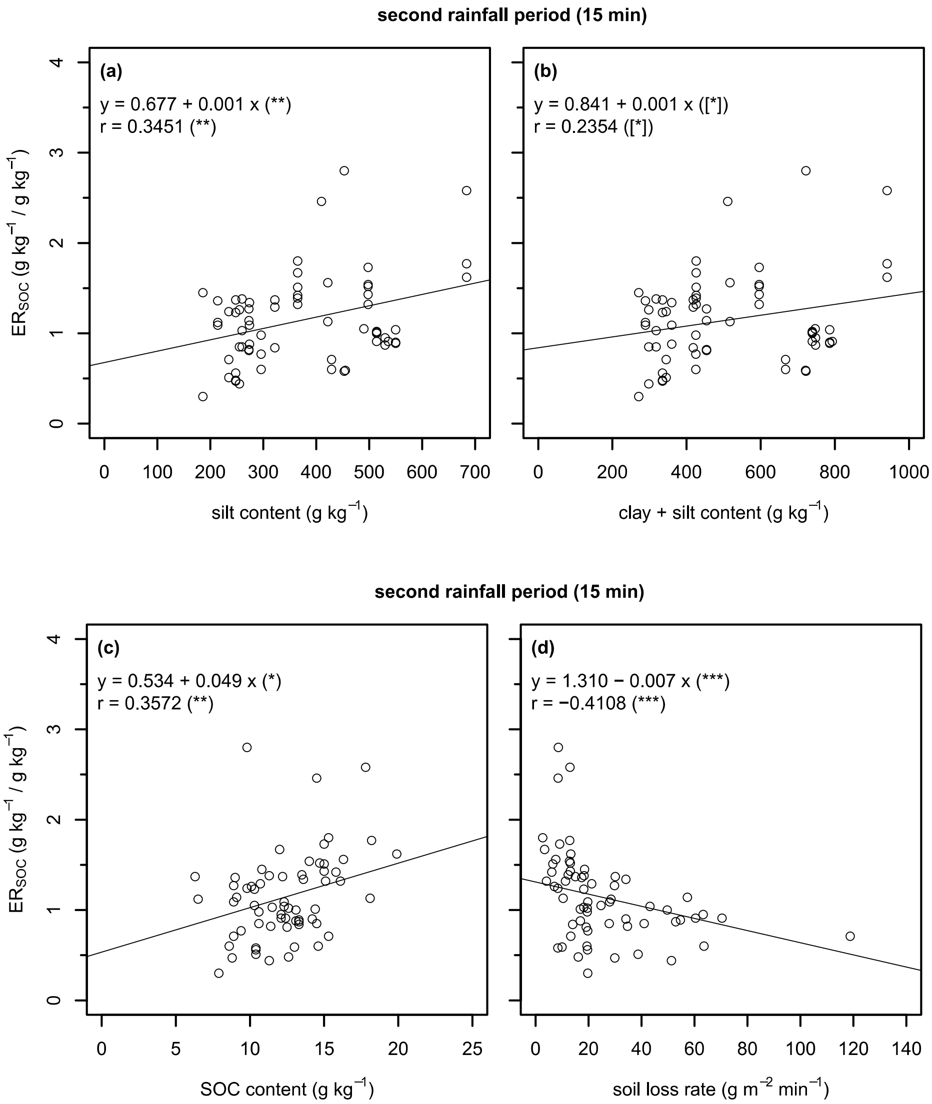

Figure 7. Simple linear regression of the soil organic carbon enrichment ratio (ER_{SOC}) in the second rainfall period (15 min) against (**a**) the silt content, (**b**) clay + silt content, (**c**) soil organic carbon (SOC) content, and (**d**) soil loss rate. For each parameter fitting, generalised linear models assuming a Gamma distribution have been applied. The regression functions and Pearson product–moment correlation coefficients (*r*) are given for each parameter fitting. The significance levels of the regression function slopes and *r*, indicating a difference from zero, are as follows: (***) $p < 0.001$; (**) $p < 0.01$; (*) $p < 0.05$; ([*]) $p < 0.1$.

4. Discussion

4.1. Relationships between the Soil Loss Rate, Soil Texture, and SOC Content

On sites with a slope inclination of >14%, the soil loss rate in the first rainfall period was mainly influenced by the silt content, clay + silt content, and SOC content (Figure 4). On average, the higher the content of these particles, the higher the soil loss rate was. In contrast, no correlation between the soil loss rate and the particle size distribution and SOC content was found for the second rainfall period (Table S2). These observations can be attributed to the preferential mobilisation and transport of fine-grained soil particles and SOC especially at the beginning of the rainfall simulation, resulting in an initial flush of small, easily erodible soil particles in the runoff [7,9,11]. Cheraghi et al. [9] showed that the fine particle (<20 µm) concentration in the runoff quickly rose and reached its peak within the first minutes of precipitation, whereas it started to decrease continuously during the first 20 min of rainfall [9]. Similarly, Asadi et al. [11] found that the contribution of finer particles to sediment concentration in the runoff was major at the beginning of simulated rainfall, whereas it decreased with ongoing rainfall [11]. Another study revealed an enrichment of particles < 20 µm in size in the eroded material and indicated that the supply of easily erodible particles was limited, since their ER in the 20 min to 40 min rainfall period was smaller than that within the first 20 min of rainfall [7]. Similarly, fine-grained particles, especially silt, were preferentially exported during the first 30 min of rainfall in our experiments, resulting in a depletion of fine particles in the source soil. The particle size distribution has been changed in the course of the first rainfall period and only a few easily erodible particles were present in the soil in the second rainfall period. The original particle size distribution had therefore only little relevance for the soil loss during the second rainfall period, a circumstance that was reflected in the absence of correlations. Regarding the SOC content, a positive correlation with silt content, clay + silt content, and clay content was found (Figure 3). This correlation conforms with other studies, and this is due to the preferential association of SOC with fine mineral particles [7,10,12,41,42]. For this reason, SOC showed a similar behaviour to the fine soil particles, i.e., high SOC content resulted in high soil loss in the first rainfall period, whereas no correlation was found between SOC content and soil loss in the second rainfall period.

On sites with a slope inclination of <14%, the relationships between the soil loss rate, soil texture, and SOC content were different than those on sites with higher slope inclinations. The soil loss rate in the first rainfall period was influenced by the SOC content such that higher SOC content caused lower soil loss (Figure 4). The soil loss rate in the second rainfall period was influenced by the clay content such that the higher the clay content, the higher the soil loss was (Figure 5). From these results it can be deduced that at the beginning of the rainfall simulations, SOC obviously acted as an effective stabiliser against erosion. Numerous other rainfall experiments have shown that higher SOC content reduces soil loss [6–8], as SOC promotes aggregate formation and increases aggregate stability, thereby decreasing the vulnerability of soil aggregates to rainfall-induced disruption [5,7,43]. The results of our experiments suggest that soil aggregates remained quite stable during the first rainfall period, thereby effectively lowering soil loss. With proceeding rainfall, however, the aggregates became gradually instable to such an extent that the erosion-reducing effect of higher SOC content was not effective anymore in the second rainfall period. This aggregate breakdown was possibly related in the first instance to clayey aggregates, since increasing clay content caused an increasing soil loss rate in the second rainfall period, but not in the first one (Figure 5, Table S2). In soils with relatively high clay content, the clay was probably well bound in aggregates and therefore not subject to preferential erosion in the first rainfall period, i.e., there was no initial flush of fine particles which would have caused higher soil loss. However, the wetted aggregates became unstable during the second rainfall period and released clay particles, which were easily erodible and resulted therefore in higher soil loss.

In summary, it seems that on sites with a slope inclination of <14%, soil organic carbon was effective in decreasing soil erosion mainly in the first 30 min of rainfall, probably by means of aggregate formation, which protected the fine soil particles from preferential erosion. On sites with a slope inclination of >14%, soil organic carbon and fine soil particles were preferentially eroded, indicating that SOC and aggregates could not diminish erosion. The reason was probably the steep slope, as it is known that a higher slope inclination causes higher soil loss [7,44].

4.2. Enrichment of SOC in the Eroded Material

For the first rainfall period, the enrichment of SOC in the eroded soil was mainly observed when the clay content, silt content, and soil loss rate were low (Figure 6). These results are in accordance with other pieces of literature [7,10,13] and indicate that preferential erosion of SOC was taking place predominantly in soils with relatively high sand contents and relatively low erosion susceptibility. Such coarse-textured soils have a small degree of aggregation and the organic matter in these soils is easily erodible [7,13,45]. This preferential erosion of SOC in sand-rich soils can be attributed to the shape and the small density of organic particles, both of which require less energy for the mobilisation and transportation of organic matter as compared to mineral particles [7].

In the second rainfall period, 17 considerably high ER_{SOC} values of $3.14 < ER_{SOC} < 9.48$ were found, which were related to the SOC contents in the eroded soil of between 40.5 g kg^{-1} and 131.4 g kg^{-1} (Table S1). With respect to the SOC contents in the original soil of only 6.3 g kg^{-1} to 19.9 g kg^{-1} (Table S1), it seems unlikely that such a tremendous enrichment of SOC, i.e., of both 'free' particulate organic matter and mineral-associated organic matter, occurred. This assumption is supported by other studies, which showed maximum ER_{SOC} values of approximately 2 [13], 3 [7], and 4 [10], respectively. Moreover, an enrichment with $ER_{SOC} > 3.14$ was found in four sites only (Solopysky 1, Solopysky 2, Věž 3, and Věž 4; Table S1). Therefore, we assume that these high ER_{SOC} values were affected by the washout of a high quantity of coarse particulate organic matter, e.g., plant residues. Such concentrations of organic matter were site-specific and were probably located within the top centimetres of the soil. In the course of the first rainfall period, overlying mineral soil particles were eroded, whereas the organic matter hotspots still remained on the site. During the second rainfall period, this organic matter was exposed on the soil surface and due to ongoing soil erosion, it was finally exported from the site. However, this suggestion needs to be proofed in future research.

When excluding the high values of $ER_{SOC} > 3.14$ from the regression and correlation analyses, the second rainfall period resulted in an enrichment of SOC in the eroded soil also mainly when soil loss rate was low (Figure 7d). This observation is similar to the one in the first rainfall period and underpins the abovementioned finding that the enrichment of SOC occurs especially in soils with low erodibility. Contrary to the first period, however, for coarse-textured soils, there was more SOC depletion and less SOC enrichment in the eroded material (Figure 7b). This circumstance led on average to a smaller ER_{SOC} in the second rainfall period than in the first one (Table 2). The reason for this observation was presumably the preferential erosion of SOC in sandy soils discussed above. The easily erodible fraction of SOC was already washed out during the first rainfall period and the remaining quantity of SOC, which was probably less erodible, was not subjected to preferential erosion in the second rainfall period.

Enrichment of SOC in the eroded soil had a non-significant tendency to decrease with the increasing SOC content in the source soil for the first rainfall period (Table S2), whereas it was positively correlated with the SOC content in the second rainfall period (Figure 7c). In general, the relationship between ER_{SOC} and SOC content was similar to the relationship between ER_{SOC} and fine particle content, especially silt content (Table S2, Figure 7a–c). Such similarity was also found elsewhere [7] and coincides with the strong correlation between SOC content and fine particle content, particularly silt content (Figure 3). Therefore, the influence of SOC content on SOC enrichment seemed to be the result of an association of SOC with fine particles, especially silt. For soils low in SOC, which are typically sandy soils, SOC was mainly not bound to mineral particles and was already easily washed out during the first rainfall period. For soils with higher SOC contents, which are usually finer-textured soils, SOC was bound to mineral particles and eroded together with them, instead of being preferentially washed out.

5. Conclusions

The analysis of 82 rainfall simulations on bare fallow soils revealed that on sites with a slope inclination < 14%, soil organic carbon was apparently effective in reducing soil loss in the first phase of rainfall. On sites with >14% slope inclination, however, any probable erosion-mitigating effect of SOC was obviously outclassed by the effect of the steep slope on soil loss. Here, soil loss was mainly driven by preferential erosion of fine-grained particles in the first phase of rainfall. In general, a low soil loss rate was coupled with relatively high enrichment of SOC in the eroded material as compared to the source soil, indicating that preferential erosion of SOC took place predominantly in soils with low erosion susceptibility.

The results suggest that SOC has some erosion-mitigating potential in bare fallow soils, which is limited by slope steepness, however. Therefore, SOC can be considered as only one element within a wider range of soil conservation measures. This study also showed that enrichment of SOC in the eroded soil depends on soil texture. Lower SOC enrichment in fine-textured eroded soils might be counterbalanced by the higher erosion rates in these soils, thus suggesting similar SOC losses independent of textural class [13]. In order to minimise SOC losses due to soil erosion, the application of soil conservation measures, including permanent soil cover and growing crops with long-term protection against soil erosion [46,47], is therefore important in all soil types.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010217/s1, Table S1: Site characteristics and results for each rainfall simulation; Table S2: Results of regression and correlation analyses.

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Publikace 13

Název

Enhancing Soil Organic Matter Transformation through Sustainable Farming Practices: Evaluating Labile Soil Organic Matter Fraction Dynamics and Identifying Potential Early Indicators.

Citace

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Enhancing Soil Organic Matter Transformation through Sustainable Farming Practices: Evaluating Labile Soil Organic Matter Fraction Dynamics and Identifying Potential Early Indicators

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Abstract: The growing global population and increasing demand for agricultural products have exerted significant pressure on agricultural systems. As a result, soil organic matter depletion and degradation have become prevalent issues, including in regions such as South Bohemia, Czech Republic, where conventional farming practices are predominant. Soil organic matter (SOM) plays a critical role in soil health, crop productivity, and the sustainability of agricultural systems, with changes occurring in both the total and labile fractions of the organic matter pools. However, changes in the total soil organic matter carbon pool (TOC) resulting from agricultural practices occur gradually and may become evident only after several years, posing challenges for timely management adjustments. Therefore, the identification of early indicators of SOM dynamics is crucial for implementing prompt corrective actions. The aim of this study was to evaluate the effects of sustainable management practices, such as cultivated crops (*Pisum sativum* and *Lupinus albus*), selected entomopathogenic and myco parasitic fungi (MEHA) (*Trichoderma virens* and *Metarhizium brunneum*), and lactic acid bacteria (LAB) on the labile fraction of the SOM pool (C_{LSOM}) and identify potential early indicators. Our findings demonstrated that the type of crop and applied microorganisms (treatments) significantly affected the C_{LSOM} in peas, and the crop growth stages affected the TOC in both pea and lupin. Growth stages also showed an impact on the C_{LSOM} in lupin. Moreover, in both crops, the change in C_{LSOM} correlated with changes in the SOM oxidation rate constant (k), carbon lability index (LI), carbon management index (CMI), and carbon enrichment ratio (ER). Conversely, changes in the TOC did not exhibit significant correlations, except for LI and CMI, which showed a positive correlation with the TOC in peas ($p < 0.05$). Furthermore, the separate application of MEHA and LAB on seeds or leaves resulted in increased SOM carbon pools compared with the combined application. The application of these beneficial microorganisms in pea and lupin crops showed potential in maintaining or increasing C_{LSOM}, which can be assessed early through indicators such as k, LI, CMI, and ER. Contributing to the development of sustainable soil management strategies, future research should further investigate different crops and microorganisms—and the mechanisms underlying their observed relationships—and explore additional early indicators to refine and optimize sustainable agricultural practices.

Keywords: carbon lability index; carbon management index; entomopathogenic fungi; lactic acid bacteria; oxidation rate constant; soil organic matter pool dynamics

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1. Introduction

Soil is the thin layer of the Earth's crust, consisting of organic and mineral components, which is influenced by bio-geophysical and chemical processes [1]. From a physical standpoint, soil is a three-phase system, consisting of solid components (organic, inorganic, and biota), liquid components (soil water and a nutrient solution), and gaseous components (soil and air), providing support for plants [2]. On a human timescale, soil is a vital, living, dynamic, nonrenewable natural resource that plays many critical functions in terrestrial ecosystems [3,4]. Recent studies have demonstrated that land use management practices have a significant impact on the soil quality and greenhouse gas emission into the atmosphere. This is particularly evident in agricultural fields, where the soil nutrients are utilized for crop growth [5,6]. Soil organic matter serves as the primary reservoir of nutrients and plays a crucial role in maintaining soil quality and health [7]. It influences the chemical, physical, and biological properties of the soil, which are essential for maintaining soil structure, fertility, water flow, microorganisms, carbon storage, and overall productivity [8]. The organic matter content of the soil is a balance between the addition and decomposition rates (turnover rates) and, as such, changes in management, land use, and land cover, can result in significant alterations in both turnover rates and the size of the organic matter pool, affecting carbon, nutrients, and agricultural productivity [9–13]. Additionally, studies have shown that the size and management outcomes of the soil organic matter pool depend on the activities of the soil microorganisms [14,15]. Although soil microorganisms differ in their cellular capabilities and metabolic requirements as decomposers, bacteria and fungi heterotrophs dominate the rest in their ability to decompose organic material in the soil [16–18]. During decomposition, fungi act as primary degraders with high enzymatic capabilities and low metabolic nutrient requirements [19–22], while bacteria have a short turnover and high metabolic activities and act as rapid recyclers of simply structured molecules that are rich in organic matter compounds [23,24]. The abundance of both microbial groups and soil physical–chemical properties significantly impacts organic matter and the carbon pool, as well as ecosystem functioning [25,26]. Furthermore, legume-based cropping systems, particularly rotations involving legumes, have been found to have a significant impact on the SOM carbon levels over both short and long durations. Legumes, characterized by their low carbon-to-nitrogen ratio, contribute easily degradable residues that enhance the soil organic matter pools [27,28]. They also stimulate soil biological activity, improve soil structure, enhance soil aeration, and increase the soil's water-holding capacity [29–31]. Among legumes, lupin (*Lupinus albus*) has demonstrated remarkable capabilities in influencing soil organic matter and microbial activity [32–35]. Lupin is well suited for maintaining soil nitrogen and organic matter contents [36], establishing symbiotic relationships with important soil microorganisms, such as bacteria and fungi, and exuding important phenolic compounds and organic acids [37]. Lupin thrives in acidic soils where most crops have difficulties growing [33], performs well in cold climates, and has a high protein content [38]. Lupin also exhibits resilience to various stresses and aids in the recovery of degraded and polluted soils [34]. Pea (*Pisum sativum*), another important legume, has shown the ability to establish beneficial relationships with lactic acid bacteria and MEHA [39–42]. It contributes to increasing SOM and maintaining yields, and it address the soil organic carbon dilemma [43].

In general, detecting small changes in the total soil organic matter carbon, especially in the short term, is difficult. Therefore, it has been proposed that sub-pools of SOM (carbon) should be used as more sensitive indicators of change [44,45]. SOM can be divided into two main sub-pools or fractions according to their level and ability to decompose, i.e., the labile and the stable fractions, although the boundaries between them are not easy to detect [46,47]. The labile fraction, also known as primary or readily oxidizable organic matter, is composed of plant and soil organisms that are partly decomposed but have not yet undergone humification. This fraction is particularly significant due to its high turnover rate, high oxidation rate, positive impact on soil fertility, and susceptibility to management practices [48]. The second sub-pool is a stable fraction, characterized by resistance to oxidation, high cation exchange capacity, and due to its recalcitrant nature, it is not affected by land use and management as a labile fraction [49,50]. These sub-pools are commonly used to study organic matter dynamics and cycling models, as decomposition rates can vary greatly [51].

Although total SOM varies depending on the cultivated crop and management practices, it is not as sensitive as its fractions, particularly the labile fraction, and especially over short durations [52–54]. Therefore, determining the most sensitive soil organic carbon pools and their early indicators in regions such as South Bohemia where SOM keeps declining due to management practices, would lead to better management choices, (re)building up the soil health, fertility, and productivity. Hence, this study investigates early indicators of changes in the soil organic matter stock using the approach of rotating crops involving pea and lupin legumes, as well as microorganisms, such as lactic acid bacteria and entomopathogenic and mycoparasitic fungi, to be able to make early management decisions and take quick remedial or corrective actions whenever needed.

2. Materials and Methods

2.1. Site Description and Experimental Method

This study was conducted as part of an ongoing experiment at the Zvíkov organic certified field (according to EU law, regularly monitored by KEZ, o.p.s. controlling organization) in České Budějovice, Czech Republic. The field is located at coordinates 48.974013 N, 14.609433 E at an altitude of 460 m above sea level. The climate in the area is characterized by comfortably warm summers and cold windy winters. It is generally partly cloudy and humid throughout the year. The temperature typically ranges from −4 °C to 24 °C, rarely dropping below −12 °C or exceeding 31 °C (Figure 1). The average long-term total annual rainfall is 623 mm, with the majority occurring during the summer months [55,56].

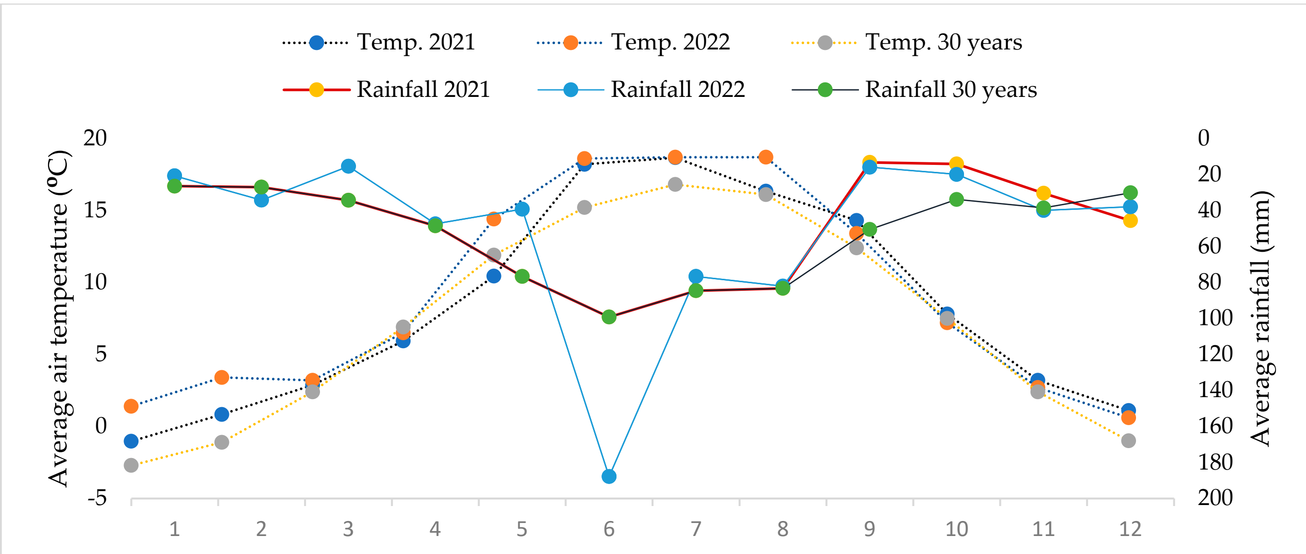

Figure 1. Monthly average air temperature and precipitation for 2021, 2022, and 30 years at the experimental location.

The soil at the experimental site is typical loamy soil (orthic Luvisol, a loamy soil with a medium particle size texture) (Table 1). The field has been under organic farming practices since 2015, spanning a period of seven years. During this time, it has been utilized for cultivating wheat (*Triticum spelta*), oats, and barley cereals rotated with clover legume. Land management and planting were carried out using conventional methods, while weeding was performed using mechanical techniques. Minimum tillage and no fertilizer were used once when only clover was planted. For this specific experiment, which took place from September 2021 to July 2022, the field was initially covered with clover (bonus variety).

During the experiment, we rotated it with pea (*Pisum sativum*) and lupin (*Lupinus albus*), and these crops were treated with *Trichoderma virens*, *Metarhizium brunneum*, and lactic acid bacteria microorganisms. Soil management practices involved methods such as mechanical and minimum tillage, weeding, and the application of composted sheep manure. As it is an organic farm, no synthetic inputs were used. The experiment followed a randomized complete block design with three replications. The factors considered were the type of crop, with two levels (peas and lupin), and the type of treatment, with nine levels (T1: control, T2: seeds treated with bacteria, T3: seeds treated with fungi, T4: leaves treated with bacteria, T5: leaves treated with fungi, T6: seeds and leaves treated with bacteria, T7: seeds and leaves treated with fungi, T8: seeds treated with bacteria and leaves treated with fungi, and T9: seeds treated with fungi and leaves treated with bacteria). This resulted in a total of 54 plots, each measuring 25 square meters.

Table 1. The Zvíkov experimental site description.

Parameter	Description
Soil type	Orthic Luvisol
Soil texture	Loamy soil
pH (H_2O)	5.7
pH ($CaCl_2$)	5.1
Electrical conductivity	0.0932 dS/m
Bulk density	1.3 g/cm^3
Soil management	Conventional methods with minimum soil disturbance
Fertilization	Composted sheep manure, 4 T/ha (8.9 Kg N/t, 5.4 kg P_2O5/t, 17.7 kg K_2O/t) No synthetic inputs
Rotation Plan	Wheat–Oat–Barley/Clover–Peas–Lupin

2.2. Fungi and Bacteria

Trichoderma virens and *Metarhizium brunneum*, obtained from the collection of the Department of Crop Production of the Faculty of Agriculture and Technology at the University of South Bohemia in České Budějovice [57], and a consortium of lactic acid bacteria from the Culture Collection of Dairy Microorganisms of Dairy Research Institute Ltd., Prague [58], were used in this experiment. All isolates were stored as live cultures on agar slants and in cryopreservatives as frozen cultures. The seeds of selected crops were coated with a suspension of these microorganisms. A suspension of *Trichoderma virens*, *Metarhizium brunneum*, and lactic acid bacteria was prepared either from an experimental batch of the preparation or from a pure culture of these microorganisms cultivated on an artificial nutrient medium. The spores were washed into an adhesive solution with which they were easily attached to the surface of the seeds. The suspension was adjusted to a standard titer of 1×10^6 spores for T. virens and *M. brunneum* and 1×10^7 lactic acid bacteria spores in 1 mL of suspension. The seeds were transferred to a container, and an adequate amount of suspension was added so that each seed was thoroughly coated with the prepared suspension.

2.3. Soil Sampling

Soil sampling was conducted at three different times: before sowing (after land preparation, during sowing time), during the vegetative growth stage, and at the harvest stage (before starting the harvesting activities). In each plot, soil samples were collected using an auger from the center and near the four corners of the plot, at a depth of 20 cm. The core samples from each plot (treatment) were mixed together thoroughly and combined into one composite sample, weighing approximately 600 g. This resulted in a total of 54 composite samples. The composite samples were then dried at a constant temperature of 60 °C until they reached a stable weight. The subsequent analyses were performed using soil samples obtained from this process [59].

2.4. Analyses

2.4.1. Total Organic Carbon

The total organic carbon (TOC) content of all samples was determined using the Primacs^{SLC} TOC analyser (SKALAR, Netherlands) with a dual oven design, allowing separate analyses of total carbon (TC) and inorganic carbon (IC). Total carbon was determined by catalytic oxidation of the sample at 1100 °C, converting the carbon present in the sample to CO_2, which was detected by the non-dispersive infrared detector. Inorganic carbon was determined by acidification of the sample in the IC reactor, which converted inorganic carbon to CO_2. TC − IC = TOC [46].

2.4.2. Labile Organic Matter

The labile fraction of soil organic matter was determined by the kinetics of the oxidation reaction of soil carbon [48,60]. Soil samples (5 flasks for 1 soil sample) were dispersed in a solution of 0.07 mol/L of $K_2Cr_2O_7$ in 12 M of H_2SO_4. Their organic compounds were oxidized at a temperature of 60 °C in a water bath. During this time, four partial samples were gradually removed from the water bath at 10 min, 20 min, 30 min, and 40 min. The amount of oxidizable carbon (C_{OX}) was then determined in the samples (automatic DL 50 Mettler-Toledo titrator, Greifensee, Switzerland). From the measured values, we calculated the reaction speed (rate) constant of oxidation (it was a first-order reaction). The temperature was then raised to 90 °C for 30 min, and then C_{OX} was determined in the sample from the last flask and designated as the labile fraction of soil organic matter (C_{LSOM}).

2.4.3. The Labile Fraction of the Soil Organic Matter Oxidation Reaction Rate (Speed) Constant (k)

As described, each sample was divided into five subsamples and oxidized at intervals of 10 min each, and the oxidizable carbon (C_{OX}), which can be designated as C_{OX1}, C_{OX2}, C_{OX3}, and C_{OX4}, was determined. This oxidizable carbon was determined during oxidation at 60 °C in a solution of 0.07 mol/L of $K_2Cr_2O_7$ in 12 M of H_2SO_4. The labile fraction of soil organic matter (C_{LSOM}) value was also determined at the end of the process at 90 °C (30 min). From the aspect of reaction kinetics, oxidation is a first-order reaction, and its rate is proportionate to the concentration of not-yet-oxidized organic matter [51]:

$$\frac{dy}{dt} = K(L-y) = K.Lz$$

L—total organic matter, *y*—oxidized portion of organic matter at time t, *K*—rate constant, and *Lz*—not-yet-oxidized organic matter at time t.

Using the integration from 0 to t, it is possible to write this equation as:

$$Lz = L.e^{-kt}$$

and after conversion to decadic logarithms, *K* will change to *k*:

$$Lz = L.10^{k}$$

For the oxidizable portion of organic matter at time t, this equation can be written as:

$$y = L\left(1-10^{k}\right)$$

The values C_{ox1}, C_{ox2}, C_{ox3}, and C_{ox4} and the differences C_{LSOM}—Cox_1, C_{LSOM}—Cox_2, C_{LSOM}—Cox_3, and C_{LSOM}—Cox_4 were calculated, and the logarithms of these differences were determined. In an orthogonal coordinate system, these logarithms were plotted on the *y*-axis against time *t* in minutes; on the *x*-axis, the rate constant "*k*" is the slope of the plotted straight line and was calculated from the relation:

$$k = 2.303.\ \text{tg}\ \alpha$$

Because tgα is the ratio of the opposite to the adjacent legs of a triangle of right angles whose hypotenuse is the plotted straight line, the calculation of the "k" is the 2.303 multiple of this ratio, and its dimension is in min. The higher the value, not only the greater the lability of C_{LSOM} and the better the quality in terms of functions in the soil (source of energy and nutrients for crops) but also the more reduced carbon and organic matter stocks in the soil.

2.4.4. Non-labile Organic Matter

A non-labile fraction of soil organic matter is composed of resistant organic compounds that do not oxidize in the solution of $K_2Cr_2O_7$ and H_2SO_4 mentioned above under the given conditions. As the value C_{LSOM} is known and TOC is known, the difference between them gives the non-labile organic matter fraction ($C_{N\text{-}LSOM}$): TOC– C_{LSOM} = $C_{N\text{-}LSOM}$ [48].

2.5. Carbon Management Index, Lability Index, and Enrichment Ratio

Based on the fact that a continuous carbon supply is a function of the total stock and lability (turnover rate), these two should be taken into consideration when developing a carbon management index. The carbon management index, lability index, and enrichment ratio were determined according to Blair et al. and Sainepo et al. [45,54], and they were formulated as follows:

$$Carbon\ management\ index\ (\mathrm{CMI}) = \mathrm{CPI} * \mathrm{LI} * 100$$

CPI is the carbon pool index, and LI is the soil carbon lability index under a particular use (treatment).

$$Carbon\ pool\ index\ (\mathrm{CPI}) = \frac{Total\ carbon\ in\ the\ treatment}{Total\ carbon\ in\ the\ reference}$$

It should be noted that the decline in carbon from a large carbon stock soil has no serious consequences compared with the loss of the same amount of carbon in a soil already depleted of carbon. The more soil that has been depleted of carbon, the more difficult it is to rehabilitate.

$$Lability\ index\ (\mathrm{LI}) = \frac{\mathrm{L}\ in\ the\ treatment}{\mathrm{L}\ in\ the\ reference}$$

$$Carbon\ lability\ of\ the\ soil\ (\mathrm{L}) = \frac{Content\ of\ labile\ carbon}{Content\ of\ non\ labile\ carbon}$$

The loss of labile carbon is of greater consequence than the loss of stable carbon.

The enrichment ratio of the labile carbon was calculated by dividing it by the total organic carbon of the same treatment (ER).

$$\mathrm{ER} = \frac{labile\ fraction\ of\ soil\ organic\ matter\ carbon}{Total\ organic\ carbon} * 100$$

In our experiment, CMI was used to monitor differences in soil carbon stock dynamics between treatments and control (reference), and it should be noted that there is no "ideal" value of CMI. The index provides a sensitive measure of the rate of change in the C dynamics of soil systems relative to the reference.

The accuracy and precision of this analytical method was proven and defined by Blair et al., Sainepo et al., and Kopecký et al. [46,54]. It also addresses the quality control (QC), instrument accuracy, recovery rates, limit of detection (LOD), and limit of quantification (LOQ) of the method.

2.6. Statistical Analyses

Analysis of variance (ANOVA) and post hoc Tukey's honestly significant difference test for multiple comparisons of means were performed using Statistica 14.0 software, TIBCO Inc., Palo Alto, CA, USA, 2021. Statistical significance was tested at $p < 0.05$. To analyze the existing correlation between the change of organic matter carbon stock in soil and selected indicators, a linear regression analysis was used as follows: (a) mean predicted values and residuals, (b) normality of unstandardized residue values ($p > 0.05$) by the Shapiro–Wilk test, (c) the existence of potential outliers by the Cook–Weisberg test, (d) the presence of autocorrelation among regression variables by the Durbin–Watson test, and (e) the significance of the regression model by the Fisher–Snedecor test.

3. Results

3.1. Fractions and Corresponding Carbon Content (%)

In general, the stages had statistically significant effects on the TOC ($p < 0.05$) (Figure 2) in both crops. Overall, the TOC in pea appeared with an average of 1.52^a, 1.49^a, and 1.41^b for the pre-seeding, harvesting, and vegetation stages, respectively. The averages for lupin were 1.54^a, 1.50^a, and 1.42^b TOC for the pre-seeding, harvesting, and vegetation stages, respectively. The treatment with the highest TOC during pre-seeding was T_2, TOC = 1.58; harvesting T_5, TOC = 1.55; and vegetation T5, TOC = 1.52. In addition, in lupin, the treatments with the highest TOC during pre-seeding were T_2, TOC = 1.58; harvesting T_5, TOC = 1.58; and vegetation T_9, TOC = 1.52.

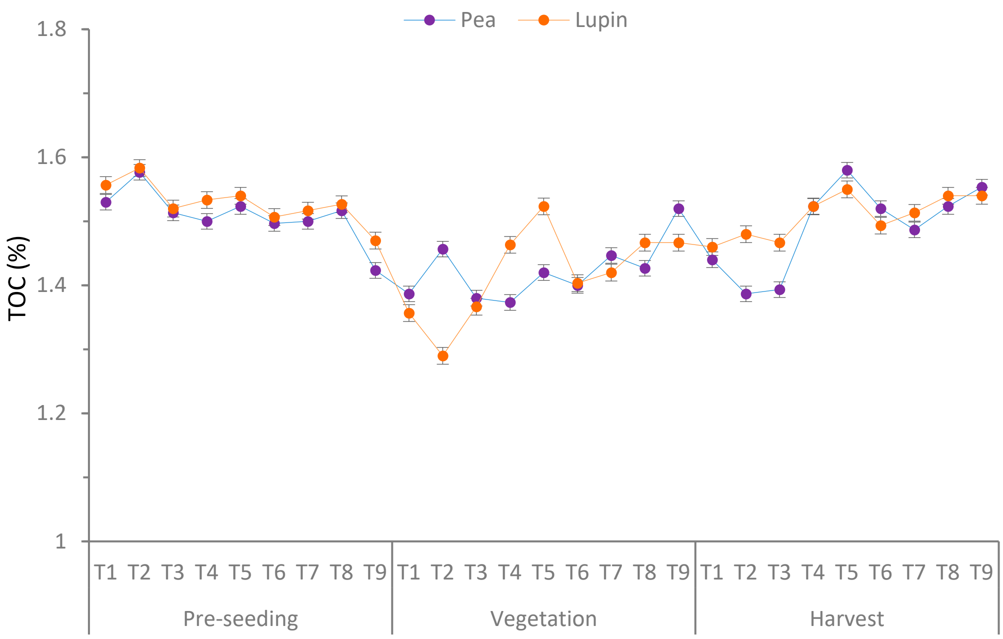

Figure 2. Effect of growing stages on total organic carbon (TOC) in two types of crops (pea and lupin) and nine different biological treatments as follows; T_1: control, T_2: seeds treated with bacteria, T_3: seeds treated with fungi, T_4: leaves treated with bacteria, T_5: leaves treated with fungi, T_6: seeds and leaves treated with bacteria, T_7: seeds and leaves treated with fungi, T_8: seeds treated with bacteria and leaves treated with fungi, and T_9: seeds treated with fungi and leaves treated with bacteria. The vertical bars denote 0.95 confidence intervals.

The results also showed that the treatments had a significant effect ($p < 0.05$) on the labile fraction of soil organic matter (C_{LSOM}) in pea, with an average of 0.87^a, 0.87^a, 0.90^{ab}, 0.89^{ab}, and 0.89^a C_{LSOM} for T_2, T_4, T_6, T_7, and T_8, respectively (Figure 3). The lowest C_{LSOM} recorded during the harvest was T_2, C_{LSOM} = 0.79; pre-seeding T_7, C_{LSOM} = 0.88; and vegetation T_6, C_{LSOM} = 0.83. The stages also had a significant effect on C_{LSOM} in lupin, with an average of 1.03^b, 0.88^a, 0.87^a C_{LSOM} for the pre-seeing, harvesting, and vegetation stages, respectively. The lowest C_{LSOM} recorded during harvest was T_9, C_{LSOM} = 0.71; pre-seeding T_5, C_{LSOM} = 0.99; and vegetation T_2, C_{LSOM} = 0.76.

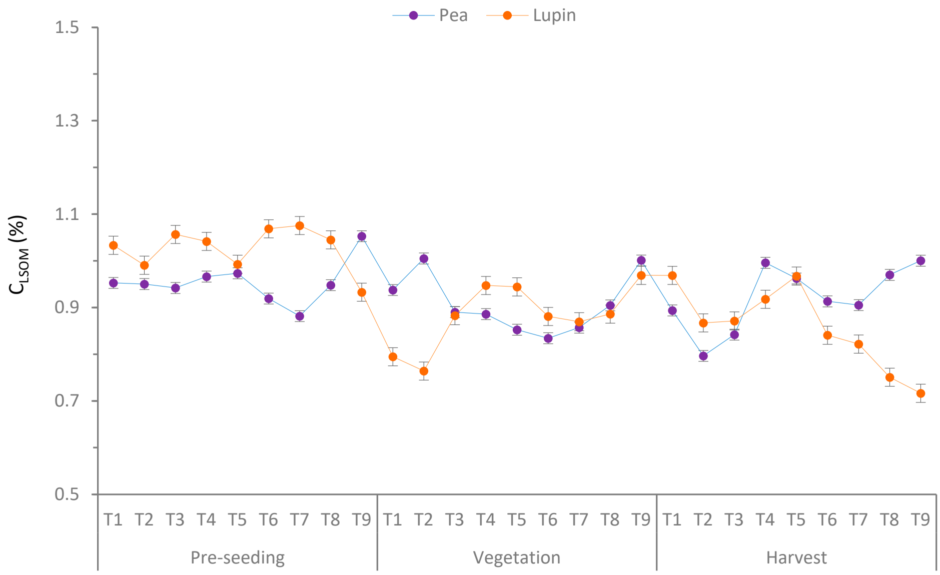

Figure 3. Effect of growing stages on labile fraction of soil organic matter (C_{LSOM}) in two types of crops (pea and lupin) and nine different biological treatments as follows; T_1: control, T_2: seeds treated with bacteria, T_3: seeds treated with fungi, T_4: leaves treated with bacteria, T_5: leaves treated with fungi, T_6: seeds and leaves treated with bacteria, T_7: seeds and leaves treated with fungi, T_8: seeds treated with bacteria and leaves treated with fungi, and T_9: seeds treated with fungi and leaves treated with bacteria. The vertical bars denote 0.95 confidence intervals.

In pea, treatments significantly affected the oxidation reaction rate constant of soil organic matter (k) ($p < 0.05$), with an average of 3.11^{b}, 3.01^{ab}, 2.96^{ab}, 2.87^{ab}, and 2.59^{abd} k for T_2, T_7, T_8, T_3, and T_5, respectively (Figure 4). The highest oxidation reaction rate constant (k) recorded during the harvesting stage was T_2, k = 3.56; vegetation T_7, k = 2.97; and pre-seeding T_7, k = 3.01, while in lupin, the highest k was obtained with values of 3.65 (T_2), 3.45 (T_7), and 3.51 (T_6), respectively, for the pre-seeding, vegetation, and harvesting stages.

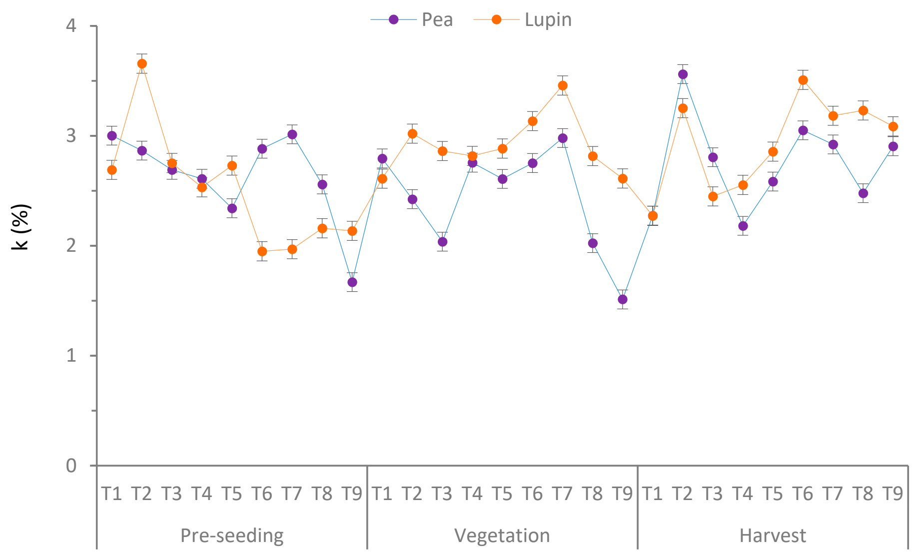

Figure 4. Effect of growing stages on the oxidation reaction rate constant of soil organic matter (k) in two types of crops (pea and lupin) and nine different biological treatments as follows; T_1: control, T_2: seeds treated with bacteria, T_3: seeds treated with fungi, T_4: leaves treated with bacteria, T_5: leaves treated with fungi, T_6: seeds and leaves treated with bacteria, T_7: seeds and leaves treated with fungi, T_8: seeds treated with bacteria and leaves treated with fungi, and T_9: seeds treated with fungi and leaves treated with bacteria. The vertical bars denote 0.95 confidence intervals.

3.2. Carbon Management Index (CMI), Carbon Lability Index (LI), and Carbon Enrichment Ratio (ER)

As shown in Figure 5, the highest CPI in pea was obtained from the pre-seeding and vegetation stages, with a value of approximately 1.01 without significant difference from each other. However, the harvesting stage in lupin showed the highest CPI, significantly higher than the two other stages. Regarding LI, the pre-seeding stage had the highest amounts in pea and lupin crops (0.97 and 1.19, respectively). Similar to LI, the highest values for CPI were also obtained in pre-seeding in both crops. The treatments and stages showed different effects on the enrichment ratio (ER) in pea; however, they were not statistically significant. In lupin, the ER was statistically different at the three stages ($p < 0.05$): pre-sowing (0.67^{b}), vegetation (0.66^{a}), and harvesting (0.58^{a}).

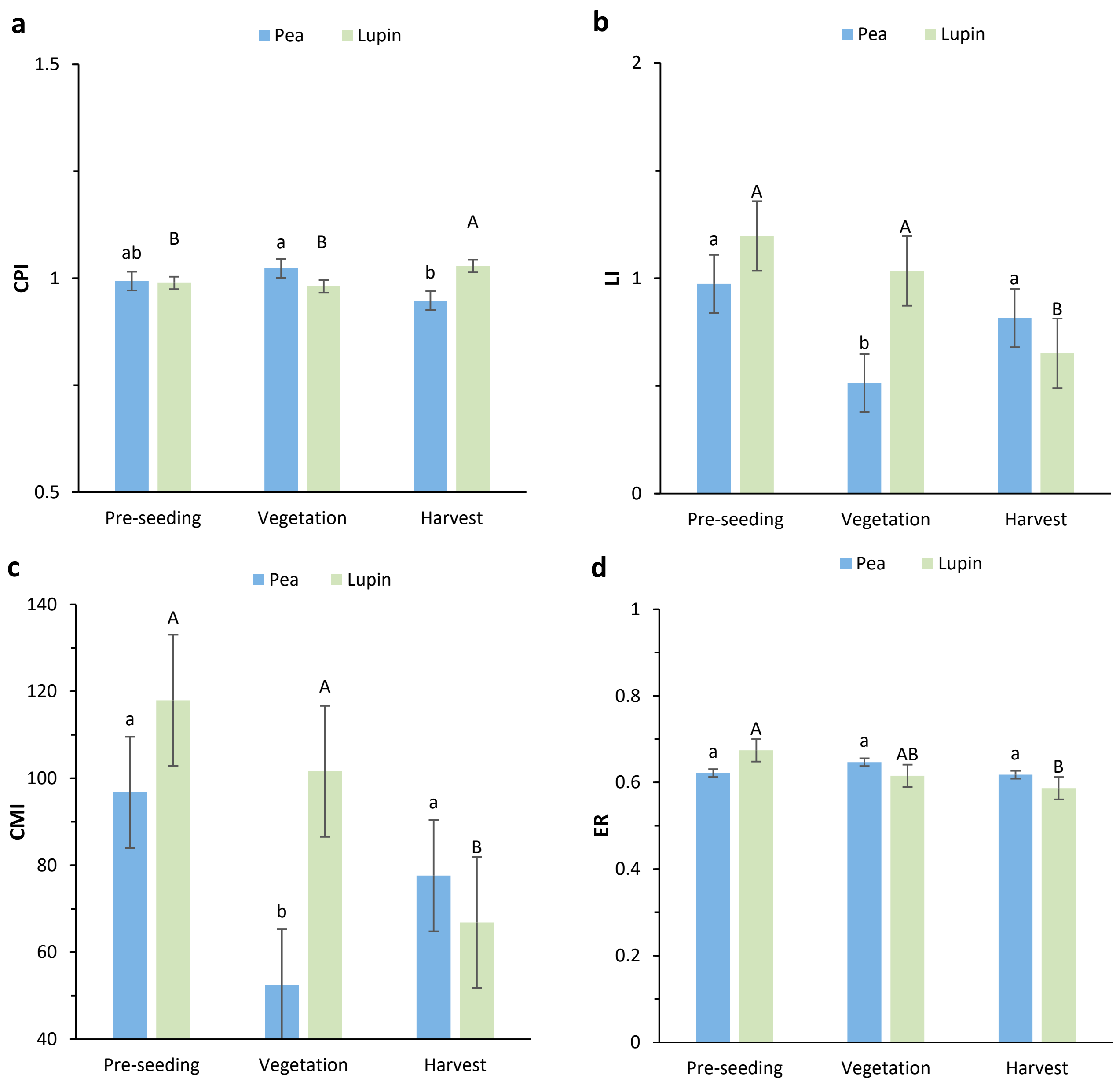

Figure 5. Effect of growing stages on carbon pool index (CPI), lability index (LI), enrichment ratio (ER), and carbon management index (CMI) in two types of crops (pea and lupin). (**a**). CPI Vs growth stages, (**b**). LI Vs growth stages, (**c**). CMI Vs growth stages, (**d**). ER Vs growth stages. The vertical bars denote 0.95 confidence intervals. Different lowercase and uppercase letters indicate significant difference between growth stages in pea and lupin, respectively.

3.3. Regression Analysis between Soil Organic Matter Carbon Stocks and Selected Indicators

The results of the regression analysis in Table 2 and Figure 6 show an apparent statistically significant correlation between the labile fraction of soil organic matter carbon (C_{LSOM}) and the four indicators (the oxidation reaction rate constant (k), carbon lability index (LI), carbon management index (CMI), and the enrichment ratio (ER)) in both crops. In addition, except for the lability index (LI) and the carbon management index (CMI), the total organic carbon (TOC) did not correlate with these indicators. A negative correlation for the oxidation rate constant was observed, but the rest of the indicators were positively correlated with the labile fraction of organic matter. The statistical characteristics of the regressions are presented in Table 2. The residuals of all models passed the Cook–Weisberg test of heteroscedasticity for the existence of potential outliers. The results of the Shapiro–Wilk test significantly showed that the residuals followed a normal distribution ($p < 0.05$). Additionally, autocorrelation among residuals was not observed with the Durbin–Watson test. The regression model is significant according to the Fisher–Snedecor model significance test. Because the mean of the residuals was close to zero, the residuals were normally distributed, and the model was better fitted.

Table 2. Details of regression analysis between carbon stocks and selected indicators.

Crops	Variables		S-W/K-S	D-W	Mean Residual	F
Pea	*k*	C_{LFOM}	0.961	2.239	0.000	F(1, 79) = 38.80
	ER	C_{LFOM}	0.139	1.345	0.000	F(1, 25) = 54.85
	LI	C_{LFOM}	0.200	1.654	0.000	F(1, 25) = 18.73
	CMI	C_{LFOM}	0.200	1.492	0.000	F(1, 25) = 27.89
	LI	TOC	0.20	1.678	0.000	F(1, 25) = 13.80
	CMI	TOC	0.2	1.03	0.000	F(1, 25) = 18.74
Lupin	*k*	C_{LFOM}	0.6	1.431	0.000	F(1, 79) = 33.40
	ER	C_{LFOM}	0.472	1.121	0.000	F(1, 25) = 106.24
	LI	C_{LFOM}	0.604	0.815	0.000	F(1, 25) = 30.007
	CMI	C_{LFOM}	0.854	0.69	0.000	F(1, 25) = 41.314
	LI	TOC	0.60	0.991	0.000	F(1, 25) = 0.116
	CMI	TOC	0.854	1.03	0.000	F(1, 25) = 0.0274

S-W: Shapiro–Wilk test, K-S: Kolmogorov–Smirnov test, D-W: Durbin–Watson test, F: Fisher–Snedecor test, C_{LSOM}: the labile fraction of soil organic matter carbon, TOC: total organic carbon, *k:* oxidation reaction rate constant, LI: carbon lability index, CMI: carbon management index, and ER: carbon enrichment ratio.

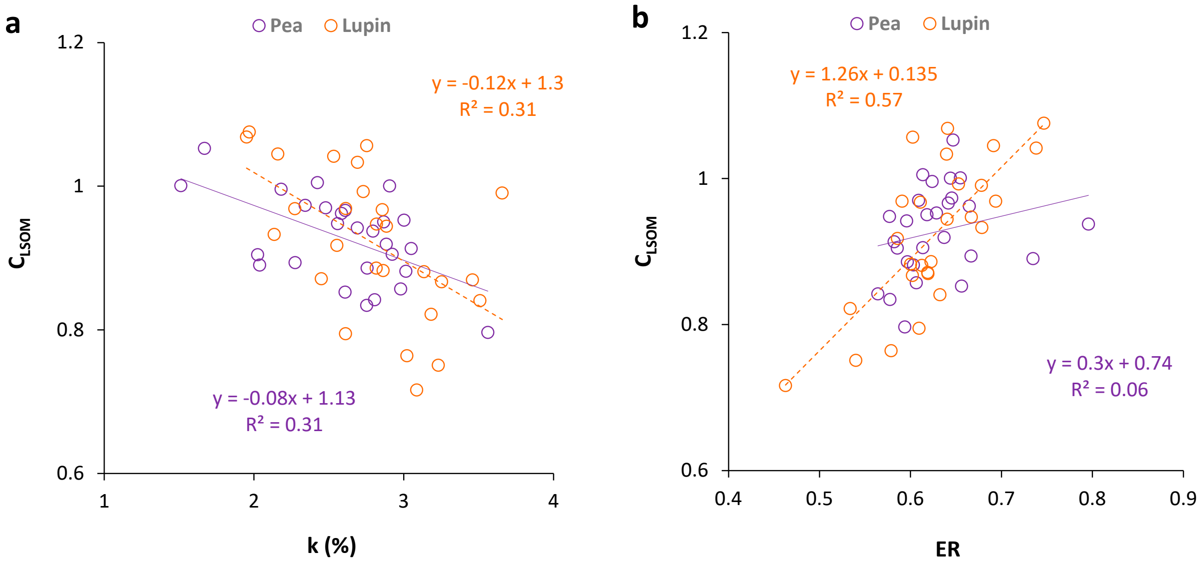

Figure 6. *Cont.*

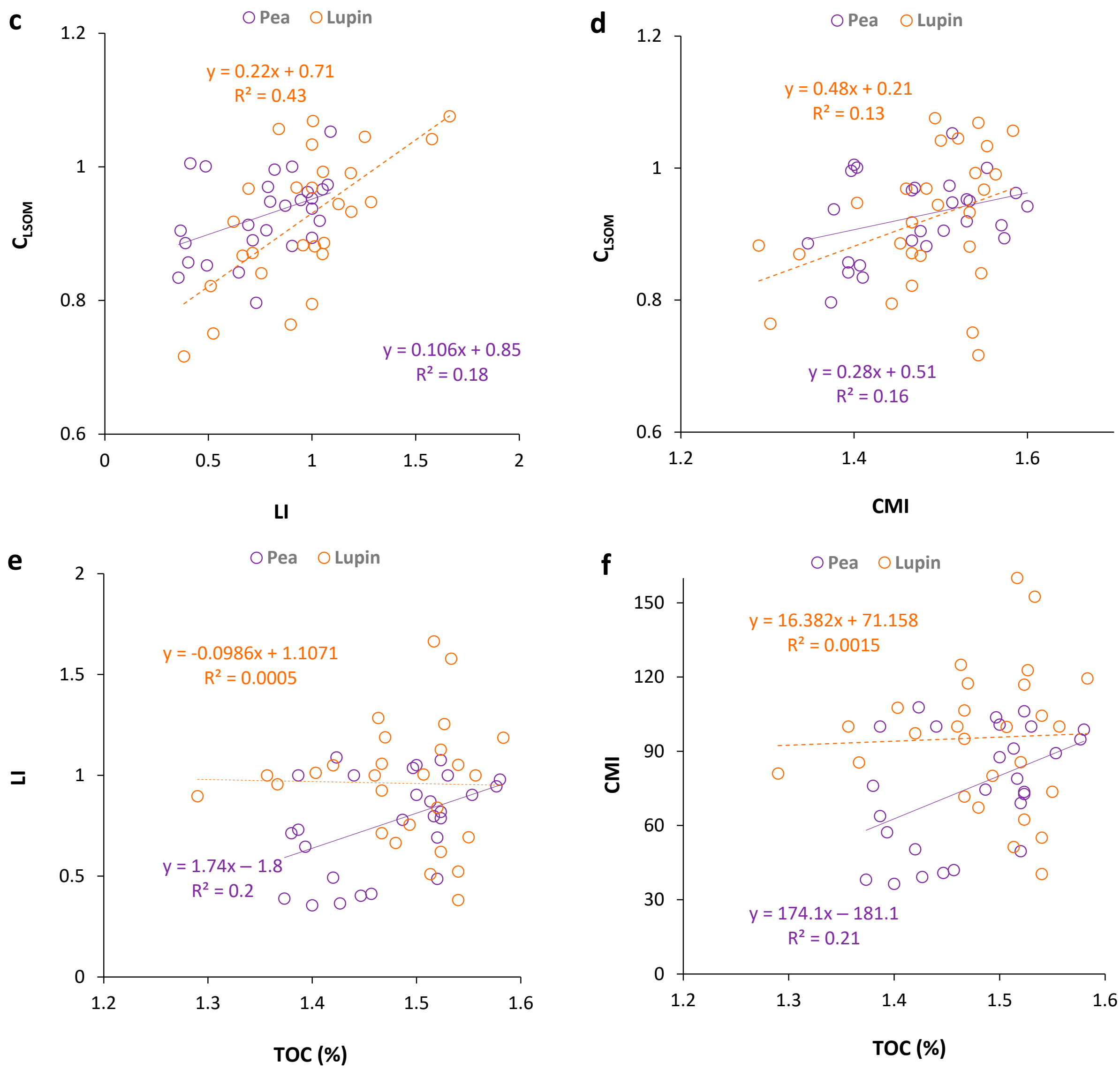

Figure 6. Regression analysis between carbon stocks and selected indicators. (**a**). C_{LsOM} Vs K, (**b**). C_{LSOM} Vs ER, (**c**). C_{LsOM} Vs LI, (**d**). C_{LSOM} Vs CMI, (**e**). LI Vs TOC, (**f**). CMI Vs TOC. C_{LSOM}: the labile fraction of soil organic matter carbon, TOC: total organic carbon, *k:* oxidation reaction rate constant, LI: carbon lability index, CMI: carbon management index, and ER: carbon enrichment ratio.

4. Discussion

4.1. Carbon Pool (TOC, C_{LSOM})

The results of this study demonstrated that cultivated crops (lupin and pea) and management practices (involving microorganisms) had a profound influence on the soil organic matter pool, especially the labile fraction (Figures 2 and 3). This interaction between cultivated crops and inoculated microorganisms was proven to improve soil fertility, nutrient cycling, and overall soil health [41,43,61]. Previous studies by Virk et al. and Van der Pol et al. [43,62] have shown that addressing the soil carbon dilemma through the inclusion of legumes in intensified rotations can enhance soil carbon while maintaining yields through a simultaneous increase in nitrogen (N) and soil organic carbon (SOC) by way of rhizodeposition, root senescence, and decomposition. Additionally, they found that legume cultivation can improve SOC levels by promoting increased microbial activity and enhancing soil structural improvement, particularly through aggregation, which is induced by the addition of organic residues with a favorable carbon-to-nitrogen (C/N) ratio. Compared with other cropping systems, legume inclusion has shown a significant potential for sequestering SOC, and the decomposition rate of legume residues is normally higher than that of cereals, thus resulting in a higher rate of SOC addition. Legume crops, such as peas and lupins, and other green manure crops contribute organic residues and enhance the carbon and nitrogen availability [30,43,63,64], while microorganisms, including entomopathogenic and mycoparasitic fungi, such as *Trichoderma virens* and *Metarhizium brunneum*, as well as lactic acid bacteria, aid in the decomposition of organic matter and crop protection, leading to increased soil organic carbon stocks [25,65,66].

The observed effect of treatments on the SOM pools may have also resulted from the soil properties, soil management, and climatic conditions (Table 1) that were conducive to microbial activities. According to Garrido-Jurado et al., Kessler et al., and others [8,67,68], soil properties, such as pH, texture, bulk density, electrical conductivity, temperature, and precipitation, significantly impact the soil microorganisms' activity, plant colonization, and soil organic matter decomposition. For instance, soil pH plays a significant role in SOM decomposition, as the production of organic acids during the process leads to a decrease in pH, particularly in the topsoil. Acidic soils tend to be dominated by fungal communities, while neutral soils create conditions favoring bacterial communities. Soil pH also influences the diversity and structure of microorganism communities, which, in turn, affect the decomposition and nitrification processes [69,70]. Electrical conductivity also increases with organic matter decomposition [71]. Soil texture influences organic matter decomposition and carbon mineralization, with a higher loam content correlating with increased pores, infiltration rate, and decomposition [72,73]. Moisture content and soil temperature also play a role, with higher levels stimulating decomposition but being dependent on the labile carbon supply and microbial activity [74,75]. The soil architecture, characterized by factors such as bulk density, affects microbial-mediated decomposition processes, as increased bulk density leads to lower soil porosity, aeration, infiltration rate, and organic matter decomposition [73,76].

The application of *Trichoderma virens*, *Metarhizium brunneum*, and lactic acid bacteria in pea and lupin crops in this experiment has positively affected the soil organic carbon pools, and specific indicators were used to detect this. For both crops, the stages significantly affected TOC, with the pre-seeding coming first, followed by the harvesting and then the vegetation stages. The dominance of the pre-seeding stage would be attributed to the fact that until harvesting, litter was accumulated on the soil, and there was no soil disturbance, but after harvesting, all straw was returned to the field. The low TOC during the vegetation stage would be due to the increased exposure of soil organic matter to microbial decomposition, accelerated residue decay from the tillage-induced aeration and plant uptake, and the conducive soil temperature, pH, and moisture. These results are similar to those of Chen et al., Li et al., Wang et al., and Zhu et al. [65,66,77,78], which showed that the return of short-term crop straw to the farm and the application of organic fertilizers enhanced the TOC in the upper soil layers. Although some studies did not find a significant effect of returning crop straw to the farm in the short durations of less than 3 years [79,80], many others have reported positive results in the long durations [63,81,82]. Although crop residues, organic fertilizers, and green manure play important roles in increasing the organic C sequestration, reducing the soil temperature fluctuation, and the conserving soil moisture [83], management practices—such as the addition of bacteria, fungi, or other effective microorganisms and minimum soil disturbance coupled with ideal environmental conditions—increase soil organic matter decomposition and mineralization [5,19,24,84–91].

In pea and lupin, the application of lactic acid bacteria, *Trichoderma virens*, and *Metarhizium brunneum* to seeds (T_2 and T_3) showed an increased TOC compared with the other treatments. However, a combined application of the two showed a significant increase in the TOC (T_6, T_8) as well, but it was less than when they were applied separately. This effect would be attributed to the fact that legume-based cropping systems result in residues that are more readily degraded (low C:N ratio), which influence soil organic matter carbon in short durations [29–31]. Furthermore, lactic acid bacteria are effective and dominate other effective microorganisms when applied together [24,84,92]. Various studies have reported increased yields and nutrient uptake where effective microorganisms, comprising lactic acid bacteria, have been applied compared with where they had not [93–95]. In addition to lactic acid bacteria, the effect shown by used fungi may be due to their ability to colonize and establish a beneficial symbiosis with many plant species, including beans and forbs [96]; soybean, corn, tobacco, and wheat [97]; and peas [98] as well as acting as primary degraders (including low-quality substrates) with high enzymatic capabilities and requiring low metabolic nutrients [22,99]. Moreover, Romaní et al. [100] studied the interactions of bacteria and fungi in the decomposing litter; although their interactions during the decomposition process were not well documented, synergistic and antagonistic interactions were detected in terms of the growth and patterns of the degradative enzymes expressed by the communities of both bacteria and fungi grown separately and together in phragmites leaves. In their experiment, the bacteria grew well when together with fungi, even though at some point, fungi growth was limited by the bacteria. The fungi performed well when alone.

Even though the TOC showed changes with some treatments, the labile fraction of soil organic matter was affected the most by the management practices. This may be attributed to the fact that the TOC is composed primarily of a stable fraction. The stable fraction is recalcitrant in nature and inaccessible to many decomposing microbes, leading to a humification process [49,101]. Hence, small changes in total soil organic matter or carbon are difficult to detect, and various authors proposed that the SOM sub-pool (labile) may serve as the early sensitive indicators of changes in the pool size [45,54,102].

The treatments in peas and the stages in lupin showed statistically significant effects on the change in the labile fraction of soil organic matter. The stages were as follows: pre-seeding first, harvesting, and then vegetation. At all stages, a single application of *Trichoderma virens* and *Metarhizium brunneum* on seeds and leaves (T_7) showed a high C_{LSOM}, followed by the single application of lactic acid bacteria on seeds and leaves (T_6) and then (T_5). Statistically significant treatments were the application of lactic acid bacteria on seeds and leaves (T_6), the application of *Trichoderma virens* and *Metarhizium brunneum* on seeds and leaves (T_7), the application of lactic acid bacteria on seeds and *Trichoderma virens* and *Metarhizium brunneum* on leaves (T_8), the application of lactic acid bacteria on leaves (T_4), and the application of lactic acid bacteria on seeds (T_2). The high change in C_{LSOM} would be attributed to the fact that this fraction of soil organic matter is more active, mineral-free, and made up of highly oxidizable, partially decomposed plant and animal residues, with a high turnover [48,60]. The more the soil is disturbed, the more the labile fraction oxidizes [5,103]. Results of this experiment showed that although the TOC in the soil was affected by management practices, C_{LSOM} was the most sensitive and was affected in the short term, as found in other studies [45,54]. Therefore, the C_{LSOM} and its lability within each management or treatment type can be used as an early indicator for soil organic matter stock dynamics [79,104–106].

4.2. Organic Matter Pool Change and Indicators (k, ER, LI, CMI)

To analyze the early indicators that can reflect the change in the soil organic matter pool, especially the most active (labile), we evaluated the organic matter oxidation rate constant, the lability index, the carbon management index, and the carbon enrichment ratio (Figure 6, Table 2). In pea, during pre-seeding, the highest lability index, the highest carbon management index, the highest carbon enrichment ratio, and the lowest organic matter oxidation reaction rate constant were found with T_9. At the harvesting stage, T_5 had a high lability index, a carbon management index, a carbon enrichment ratio, and a lower organic matter oxidation rate constant. T_3 had the same trend during the vegetation stage. In lupin, during pre-seeding, the highest lability index, the highest carbon management index, the highest carbon enrichment ratio, and the lowest organic matter oxidation rate constant were found in T_7. At the harvesting and vegetation stages, T_6 and T_4, respectively, had the same trend as the pre-seeding stage. The same trend of results was obtained by Blair et al. [45] while studying soil carbon fractions based on their degree of oxidation and developing a carbon management index for agricultural systems; by Vieira et al. [107], studying the carbon management index based on the physical fractionation of soil organic matter in an acrisol under long-term no-till cropping systems; by Sodhi et al. [108], studying how to use the carbon management index to assess the impact of compost application on changes in soil carbon; and by others [54,109]. The highest C_{LSOM} observed, the highest lability index, the highest carbon management index, the highest carbon enrichment ratio, and the lowest organic matter oxidation rate constant, especially in treatment numbers 9,5,3,7,4, and 6 compared with the control (reference), can be attributed to the increased activities of the applied lactic acid bacteria, *Trichoderma virens* and *Metarhizium brunneum,* legumes plants, straw return, and organic fertilizers. The same results were observed by Six et al. [110] while studying the sources and composition of soil organic matter fractions between and within soil aggregates; by Wu et al. [111] while studying microbial interactions with dissolved organic matter and how it drives carbon dynamics and community succession; by Bot and Benites [8] on the importance of soil organic matter (the key to drought-resistant soil and sustained food production); and by others.

Regression analyses were then performed to determine whether there was a significant correlation between the change in the SOM pool and these selected indicators (Table 2 and Figure 6). Apart from the lability index and the carbon management index that showed a positive correlation with TOC in pea, the rest of the indicators did not correlate with the total organic carbon in either crop, while the labile fraction of soil organic matter was correlated with all these indicators in both crops. This shows the ability of C_{LSOM} to predict SOM dynamics in general. For both crops, *k* was negatively correlated with C_{LSOM}, showing that the increase in the oxidation rate constant reduced the labile fraction of soil organic matter (Kopecký et al., 2021). The rest of the indicators showed a positive correlation with C_{LSOM} in both crops, indicating that the increase in the lability index, carbon management index, and carbon enrichment ratio resulted in an increased labile fraction of soil organic matter. There was a significant correlation between the change in the selected indicators and the changes in the carbon stocks. These indicators were studied and confirmed to be useful in evaluating the soil organic matter dynamics in different agricultural systems by various other researchers [45,48,54,60,112–114].

The results of this study provide insights into the influence of crop selection and sustainable management practices involving microorganisms (effective ones) on the soil carbon pool. The legume crops inoculated with microorganisms showed the ability to improve the soil organic matter pool, which may affect the soil fertility, nutrient cycling, and overall soil health. It should be added that the soil properties also played a significant role in the soil microorganism activity and organic matter decomposition. The labile fraction of soil organic matter was found to be the most sensitive to management practices, and indicators such as the lability index, carbon management index, carbon enrichment ratio, and organic matter oxidation rate constant were used to assess the changes in the organic matter pool. Although the effectiveness of these practices may vary in different conditions, it is important to note that in temperate regions like South Bohemia, Czech Republic, the soil organic matter addition and decomposition rates are generally slower compared with tropical regions [8]. Furthermore, considering the declining trend of soil organic matter in this region due to agricultural intensification using conventional methods, there is a need to adopt sustainable management practices that would address this issue [5,115]. The practices implemented in this study can be seen as a step towards addressing this issue and promoting sustainable soil management in the region. Overall, these findings emphasize the importance of crop selection, microbial inoculation, and soil management practices in enhancing the soil carbon pools and improving agricultural sustainability. Specific practices and their effectiveness may vary depending on the local conditions, crops grown, and farm management systems. It is essential to tailor these practices to the specific needs and constraints of a specific region when considering the long-term sustainability of agricultural production.

5. Conclusions

In conclusion, this study highlights the significant influence of sustainable management practices, including cultivated crops and applied microorganisms, on the dynamics of organic matter. Our results showed that treating legume crops, such as pea and lupin, with entomopathogenic and mycoparasitic fungi (*Trichoderma virens* and *Metarhizium brunneum)* and lactic acid bacteria in agricultural farms influences the soil organic matter pools, particularly $C_{\mathbf{LSOM}}$. The labile fraction of the soil organic matter (**C_{LSOM})** fluctuated greatly and was high across all treatments as well as during the pre-seeding stage compared with the other stages. This was attributed to the input of crop straw, organic fertilizer application, conducive environment, soil properties, low disturbance in most of the growing season, and the increased activities of applied microorganisms. When assessing the sensitivity of organic matter, especially **C_{LSOM}**, to the treatments, the indicators CMI, ER, LI, and *k* showed the capability to serve as early indicators that can alert us to changes in the SOM stocks, which would help in determining the right action to take. This study showed that lactic acid bacteria, entomopathogenic and mycoparasitic fungi particularly *Trichoderma virens* and *Metarhizium brunneum*, and returning crop straw to the farm should be practiced in agricultural fields to enhance the status of organic matter, decomposition (labile pool), and mineralization of the nutrients, hence improving the health and fertility of the soils. As all indicators (CMI, ER, LI, and *k*) clearly showed sensitivity to the treatments, we conclude that **C_{LSOM}** and selected indicators are promising to monitor the effects of farm management practices on the organic matter dynamics and soil quality in short durations. We, therefore, recommend further testing to evaluate the soil organic matter dynamics across a wide range of soil management practices, including different types of tillage and crops, crop rotation, intercropping, and integration of effective microorganisms.

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Article

Assessment of Soil Organic Matter and Its Microbial Role in Selected Locations in the South Bohemia Region (Czech Republic)

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Abstract: Organic matter has a very important function in soil, without which, soil formation processes cannot take place properly. It can be divided and classified based on several aspects; the most general division is between the living and non-living parts of organic matter. The results presented in this paper specifically refer to the living microbial part of organic matter. This research was carried out in the years 2021–2024 in the South Bohemia region located in the Czech Republic. Two types of land use (four permanent grassland areas, two forest areas) were evaluated. Based on laboratory soil analyses, some significant dependencies were found. For example, in grasslands with statistically identical pH, there was a dependence (p-value 0.05) between soil organic carbon (SOC), carbon of microbial biomass (MBC) and microbial basal respiration (MBR). Additionally, coniferous forest experimental locations had a lower pH, which, in turn, slowed the activity of microorganisms and promoted the accumulation of SOC in the soil. The results from this experiment support the current knowledge of organic matter and are important for a better understanding of the soil organic matter cycle.

Keywords: soil science; microorganisms; organic carbon; microbial biomass; basal respiration

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1. Introduction

Organic matter, only being a small part of soil, plays a key role because the decomposition, mineralisation and subsequent humification of organic material are among the most important soil processes affecting soil fertility and quality [1,2]. It is an important material derived from plant and animal sources [3] and has an effect on the following aspects of soil: (1) improving structure: it helps aggregate soil particles, which improves the stability of soil aggregates and increases soil porosity [4]; (2) nutrient source: organic matter contains nutrients that it releases when it decomposes [5]; (3) increasing soil retention: it gives soil a better ability to retain water [6]; (4) reduction of erosion and surface runoff [7,8]; and (5) providing a source of energy for microorganisms: it is the main source of feed and nutrients for soil microorganisms [9].

The total amount of organic matter in soil can be influenced in the long term by management practices [10]. The use of organic fertilisers, intercrops, deep-rooted crops and ploughing puts crop residues back into the soil and contributes to enriching soil with organic matter [7,10,11]. Conversely, a lack of organic matter input into soil and the loss of organic matter are behind some serious degradation processes [12].

The basic general division of organic matter is into its non-living and living parts. The non-living part of soil organic matter is divided according to the degree of decomposition [13] and the presence of non-humified soil organic matter comprising undecomposed organic matter. This includes the remains of plants (leaves, roots) and animals whose original structure is retained [9,14]. Another part consists of partially decomposed organic matter that has already been altered by soil organisms [15]. The next part is fully decomposed organic matter, which, in later stages, is referred to as humus [16]. This decomposed organic matter no longer shows signs of its original structure [17].

The living part of soil organic matter can be divided as follows: microflora [18], microfauna, mesofauna, macrofauna and megafauna [19]. This classification includes a range from smallest to largest, i.e., from micrometres to centimetres and, in some cases, up to metres [20]. Microfauna and microflora inhabit water-filled pores and water films around soil particles [21]. Mesofauna occur in existing air-filled pore spaces and are largely confined by these spaces. Macrofauna have the ability to create their own spaces through their activities and, like megafauna, can significantly influence the coarse structure of soils [22,23]. The biodiversity in soils is impressively large [24,25] and, therefore, species with similar biology and morphology are often grouped together for classification purposes [26]. The most abundant species are among the microbial component of soil [19]. When assessing the living microbial part of organic matter, the basic parameters evaluated include microbial basal respiration (MBR) and microbial biomass carbon (MBC). These parameters have been monitored by a number of authors [27–29] and are, therefore, also evaluated in this paper.

Of course, many variables enter into the whole process of microorganism activity [30,31]. For example, temperature [32,33], soil moisture [34,35], pH [36], nutrient availability [37,38], redox potential [39] and carbon/nitrogen ratio [40] are known to be the main factors that contribute to microbial activity.

Differences can also be expected for different types of land use [41,42]. Microbial activity is particularly important for land use types where soil is the basis for management, i.e., mainly agricultural land and forests, possibly also in other ecological systems [43]. The concept of agricultural land is general and includes different types of land cover. In soil environments where disturbance is frequent (typically conventional arable land management), it is more difficult to draw general conclusions, as a number of different agricultural operations can be used during cultivation that have a significant impact on soil parameters [44]. For this reason, grasslands and forests are the subject of the current assessment as they have a relatively stable soil environment and there is an assumption of less inter-annual variation.

The aim of this study was to verify the following hypotheses: (1) soil microbial activity will vary in permanent grassland and forest locations; (2) microbial activity assessed by MBR and MBC is dependent on the amount of soil organic carbon (SOC); and (3) the amount of SOC in soil is influenced by the pH level.

2. Materials and Methods

Six soil samples from South Bohemia (49°05′00.0′′ N, 14°40′00.0′′ E) in the Czech Republic were tested every year in 2021–2024 (Figure 1). Four soil samples were from agricultural land (grassland) and two were from coniferous forest soil. Soil texture at each location listed in Table 1 was determined using the hydrometric method. This method is based on the principle of measuring the sedimentation rate of soil particles in a water environment. A hydrometer (an instrument for measuring the density of the suspension) was used to record the concentration of particles in the water at various time intervals. This makes it possible to measure the proportion of each fraction and thus determine the soil texture. The subsequent classification was performed using the texture triangle [45], which is also currently used in the Czech Republic.

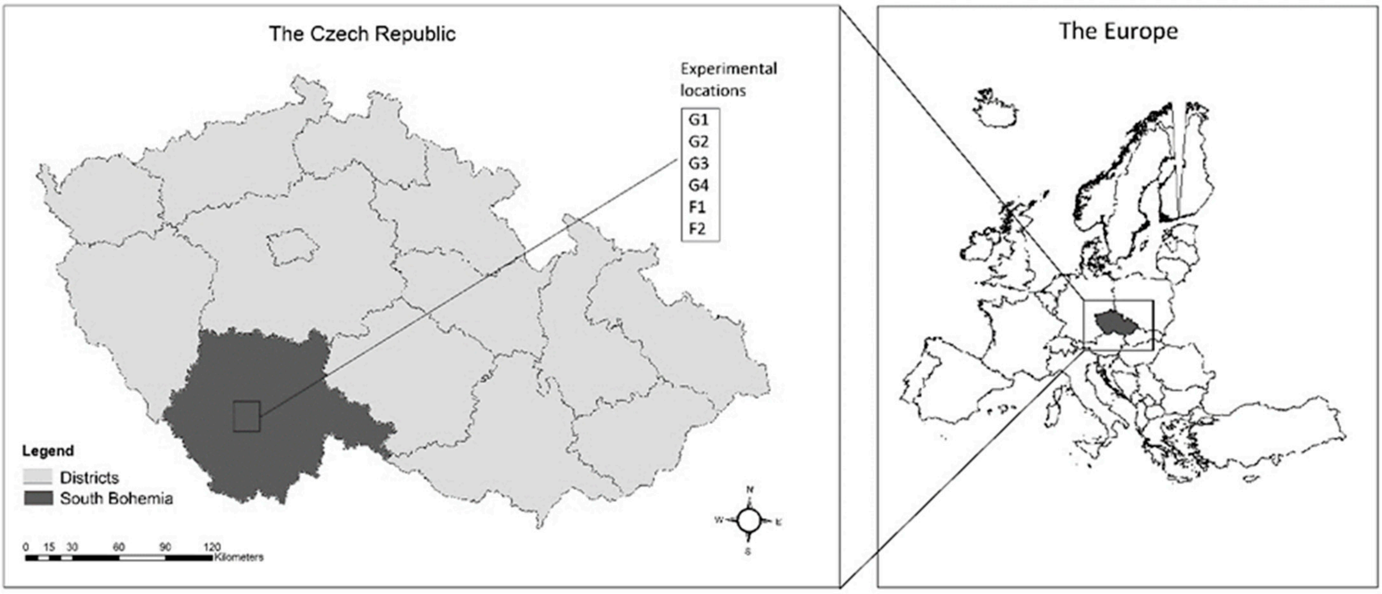

Figure 1. Map of the Czech Republic and the district of South Bohemia.

Table 1. Experimental locations.

Locations	Type of Location	Soil Texture (USDA *)
G1	Grassland	Sandy Loam
G2	Grassland	Sandy Loam
G3	Grassland	Sandy Loam
G4	Grassland	Loam
F2	Forest (coniferous)	Sandy Loam
F1	Forest (coniferous)	Sandy Loam

* USDA—U.S. Department of Agriculture: texture triangle.

One composited soil sample was taken from each locality with a spade and placed in paper bags. The composited sample consisted of a total of 5 samples from a 10 × 10 m area. The depth of sampling was 0–15 cm and the amount of soil sampled from each location was approximately 3 kg. It should be mentioned that forest locations usually have an organic horizon, which has a strong influence on the amount of SOC in the soil. When taking soil samples, the emphasis was always on doing everything the same way every year. First, the organic horizon was carefully removed and then the topsoil was taken. Nevertheless, it was difficult to ensure the uniformity of the sampling. This problem can be clearly seen in Table 2, where the standard deviation is higher for forest locations than for grassland. In the case of grassland, the top layer containing live plants was removed. Subsequently, soil sampling was carried out using a spade.

After sampling, material from the composite soil samples was taken to the laboratory and used for subsequent analyses. Samples were air-dried so that they could be sieved and then particles larger than 2 mm were removed. The soil intended for pH and SOC analysis was dried at 60 °C to a constant weight before analysis. Part of the remaining soil was homogenised and sieved through a 0.25 mm sieve. Soil sieving was conducted because some analyses were performed on soil textures less than <2 mm (pH, MBR, MBC), while SOC was analysed on a fraction < 0.25 mm.

Table 2. Results from the experimental plots (2021–2024).

Locations	pH		SOC		MBR		MBC		MMQ—qCO_3	
	(KCl)	SD	(%)	SD	(µg $CO_2 \cdot g^{-1} \cdot h^{-1}$)	SD	(µg·g^{-1})	SD	($\times 10^{-4}$ MBR:MBC)	SD
G1	4.90	0.19	3.93	0.18	0.3034	0.0203	756	65	4.1	0.6
G2	4.77	0.28	2.52	0.25	0.1621	0.0112	354	38	4.6	0.6
G3	4.66	0.12	2.36	0.23	0.1589	0.0160	301	23	5.3	0.5
G4	4.70	0.09	3.44	0.35	0.2271	0.0243	577	37	4.0	0.7
F1	3.22	0.05	7.37	1.10	0.1021	0.0284	141	18	7.4	2.2
F2	3.32	0.09	7.28	1.74	0.1333	0.0143	181	42	7.9	2.7

Standard deviation (SD), soil organic carbon (SOC), carbon of microbial biomass (MBC), microbial basal respiration (MBR), microbial metabolic quotient (MMQ).

Individual analyses of soil samples were carried out using the following procedures:

- Soil pH (ISO 10390:2005 [46])— was determined using a 1 M KCl solution. In 250 mL plastic bottles, 10 g of soil was weighed and 50 mL of KCl was added. Subsequently, the samples were shaken for 60 min on a shaker. The pH was then measured using the SI Analytics Lab 875P (Xylem Analytics, Weilhem, Germany). The measurements were carried out in two repetitions each time.
- SOC—the basis of the analysis was the method of Tyurin [47], where the process of determination was as follows: 0.1 g of soil (<0.25 mm) was weighed in triplicate for each location. Subsequently, 0.3 M $K_2Cr_2O_7$ and concentrated H_2SO_4 were mixed to form a chromosulfur mixture. The titration cups with the weighed soil were added to 12.5 mL of the chromo sulphur mixture and then the samples were burned in an oven at 135° for 30 min. Then, titration was performed using 0.2 M Mohr's salt ($(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O + H_2SO_4$) on the Mettler Toledo DL55 titrator (Mettler Toledo, Schwerzenbach, Switzerland).
- MBR—the analysis was based on the ISO standard 16072:2002 [48], but some modifications were made in the determination (soil moistening). The procedure was as follows: 150 g of soil moistened to 50% retention capacity was pre-incubated for 3 days and then 25 g of soil was weighed into breathable bags (in three replications). The breathable bags were hung in a 750 mL sealed glass bottle with 20 mL of 0.05 M NaOH at the bottom for 3 days. Before titration, 2 mL of 0.5 M $BaCl_2$ and phenolphthalein were added. Subsequently, titration was performed on the Mettler Toledo DL55 titrator (Mettler Toledo, Schwerzenbach, Switzerland) using 0.1 M HCl.
- MBC—the analysis was performed according to the ISO standard 14240-2:1997 [49] with some modifications (the weighing and moistening of the soil): 250 g of soil moistened to 50% retention capacity was pre-incubated for 3 days and then 25 g of soil was weighed (in six replications). Three samples were fumigated in a desiccator using boiling chloroform and left in the dark for 24 h. To the remaining samples, 200 mL of 0.5 M K_2SO_4 was added, and the samples were shaken for 30 min. The same process was carried out for the fumigated samples after 24 h. MBC was determined by dichromate oxidation. All samples were filtered and 8 mL was taken. Subsequently, 2 mL 0.07 M $K_2Cr_2O_7$ and 15 mL acid mixture (H_2SO_4, H_3PO_4) were added. After refluxing for 30 min, titration was carried out using 0.04 M Mohr's salt ($(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O + H_2SO_4$) on the Mettler Toledo DL55 titrator (Mettler Toledo, Schwerzenbach, Switzerland).
- Microbial metabolic quotient (MMQ)—this was the ratio between the MBR and the MBC, where the MBR was divided by the MBC.

A basic statistical evaluation was performed on the results to obtain significant correlations using one-way ANOVA. The Pearson correlation coefficient was also determined for the processed data. This correlation coefficient was evaluated if there were at least two distinct locations in the statistical evaluation.

3. Results

3.1. Soil Reaction (pH) in Experimental Locations

The basic analysis performed was the determination of pH. The results of the measurements are shown in Figure 2 and Table 2. Statistically significantly higher values were measured at the grassland locations compared to the forest locations (Table 3). The highest pH across the grasslands was measured at G1 (4.90). The lowest value was at G3 (4.64). Locations G2 and G2 fell within this range in their values. Statistical evaluation of all grasslands showed no significant difference. They were therefore identical in terms of pH. Statistical agreement was also valid for the forest locations, where the mean pH for F1 was 3.22 and that for F2 was 3.32 (Table 3). The values and standard deviations (Table 2) across research years could be considered relatively stable in the locations. The highest standard deviation was measured at G2 (0.28), but this was not a significant fluctuation. Lower values were measured at the other locations.

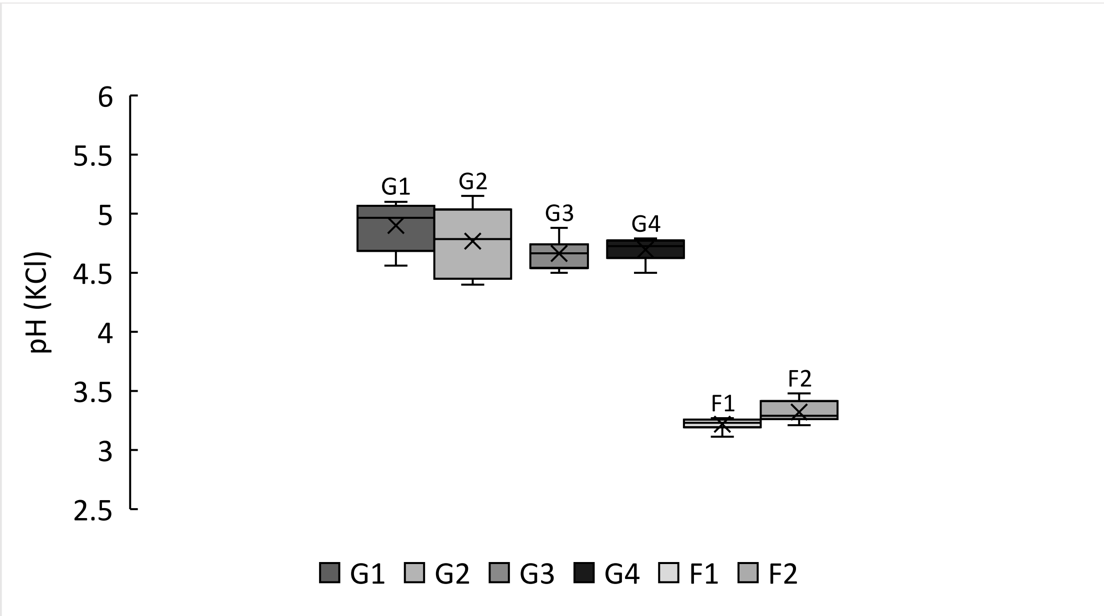

Figure 2. Soil reaction in experimental locations (box plots).

Table 3. Statistical evaluation of selected parameters (one-way ANOVA, *p*-value <0.05).

Parameters	Locations	G1	G2	G3	G4	F1	F2
pH	G1	x	6.08×10^{-1}	7.14×10^{-2}	1.64×10^{-1}	1.27×10^{-11}	1.27×10^{-11}
	G2	x	x	8.14×10^{-1}	9.56×10^{-1}	1.27×10^{-11}	1.27×10^{-11}
	G3	x	x	x	9.99×10^{-1}	1.27×10^{-11}	1.27×10^{-11}
	G4	x	x	x	x	1.27×10^{-11}	1.27×10^{-11}
	F1	x	x	x	x	x	8.19×10^{-1}
	F2	x	x	x	x	x	x

Table 3. *Cont.*

Parameters	Locations	G1	G2	G3	G4	F1	F2
SOC	G1	x	3.75×10^{-3}	9.14×10^{-4}	7.58×10^{-1}	2.50×10^{-11}	2.81×10^{-11}
	G2	x	x	9.98×10^{-1}	1.44×10^{-1}	2.29×10^{-11}	2.29×10^{-11}
	G3	x	x	x	5.33×10^{-2}	2.29×10^{-11}	2.29×10^{-11}
	G4	x	x	x	x	2.30×10^{-11}	2.30×10^{-11}
	F1	x	x	x	x	x	1.00×10^{-0}
	F2	x	x	x	x	x	x
MBR	G1	x	3.22×10^{-11}	3.22×10^{-11}	5.85×10^{-11}	3.22×10^{-11}	3.22×10^{-11}
	G2	x	x	9.99×10^{-1}	2.56×10^{-9}	2.71×10^{-8}	1.55×10^{-2}
	G3	x	x	x	5.70×10^{-10}	1.25×10^{-7}	4.37×10^{-2}
	G4	x	x	x	x	3.22×10^{-11}	3.23×10^{-11}
	F1	x	x	x	x	x	7.31×10^{-3}
	F2	x	x	x	x	x	x
MBC	G1	x	2.29×10^{-11}	2.29×10^{-11}	2.30×10^{-11}	2.29×10^{-11}	2.29×10^{-11}
	G2	x	x	3.26×10^{-2}	2.29×10^{-11}	2.29×10^{-11}	2.31×10^{-11}
	G3	x	x	x	2.29×10^{-11}	2.45×10^{-11}	2.16×10^{-8}
	G4	x	x	x	x	2.29×10^{-11}	2.29×10^{-11}
	F1	x	x	x	x	x	1.96×10^{-1}
	F2	x	x	x	x	x	x
MMQ	G1	x	9.45×10^{-1}	3.90×10^{-1}	1.00×10^{-0}	2.83×10^{-5}	9.86×10^{-7}
	G2	x	x	9.05×10^{-1}	9.00×10^{-1}	7.48×10^{-4}	3.29×10^{-5}
	G3	x	x	x	3.11×10^{-1}	1.96×10^{-2}	1.34×10^{-3}
	G4	x	x	x	x	1.64×10^{-5}	5.55×10^{-7}
	F1	x	x	x	x	x	9.54×10^{-1}
	F2	x	x	x	x	x	x

Locations that were statistically equal are highlighted. Soil organic carbon (SOC), carbon of microbial biomass (MBC), microbial basal respiration (MBR), microbial metabolic quotient (MMQ). The light grey colour in the table indicates statistically identical locations.

The results from this analysis were very important for the subsequent evaluation because it was possible to divide all assessed locations into two groups with statistically identical pH. Forest locations represented one group and grasslands represented the second group. This made it possible to evaluate the effect of different pH on the other assessed parameters (SOC, MBC, MBR, MMQ). As shown in the following Sections 3.2 and 3.3, this fact proved to be very important for some parameters.

3.2. Relationship Between pH and SOC

SOC, like pH, is an essential parameter in the assessment of soil parameters. The highest amount of SOC was found at the forest locations, where the average value was 7.37% at F1 and 7.28% at F2. In this context, it should be added that the method of soil sampling mattered because as the amount of organic horizon (for forest locations) in the soil sample increased, so did the amount of SOC. It was problematic to ensure the same amount of organic horizon in the soil samples. This can be clearly seen in the standard deviations (Table 2), which were higher for forest locations than for grasslands. These facts need to be taken into account when comparing the results with other studies. In the statistical evaluation, the values from forest locations (F1 and F2) were identical (Table 3). When comparing them with grasslands, they were significantly different (p-value < 0.05). The individual grassland locations, however, did not have statistically the same SOC content, confirming that the whole issue was much more complex. The highest SOC value was measured at G1 (3.93%). This location was statistically identical to G4 (3.44%) but significantly different from G2 (2.52%) and G3 (2.36%). Locations G2, G3 and G4 could be considered identical (Table 3).

Correlations were determined at all locations but also separately for grasslands and forests (Figure 3). In the case of the forest locations (F1, F2), which were statistically identical, correlations were not assessed further. When all locations were assessed, the strongest correlation was obtained between pH and SOC. Specifically, a strong inverse correlation (−0.913) was found, meaning that the lower the pH, the higher the SOC content of the soil. For this statement, the depth of sampling needs to be considered (see Discussion chapter).

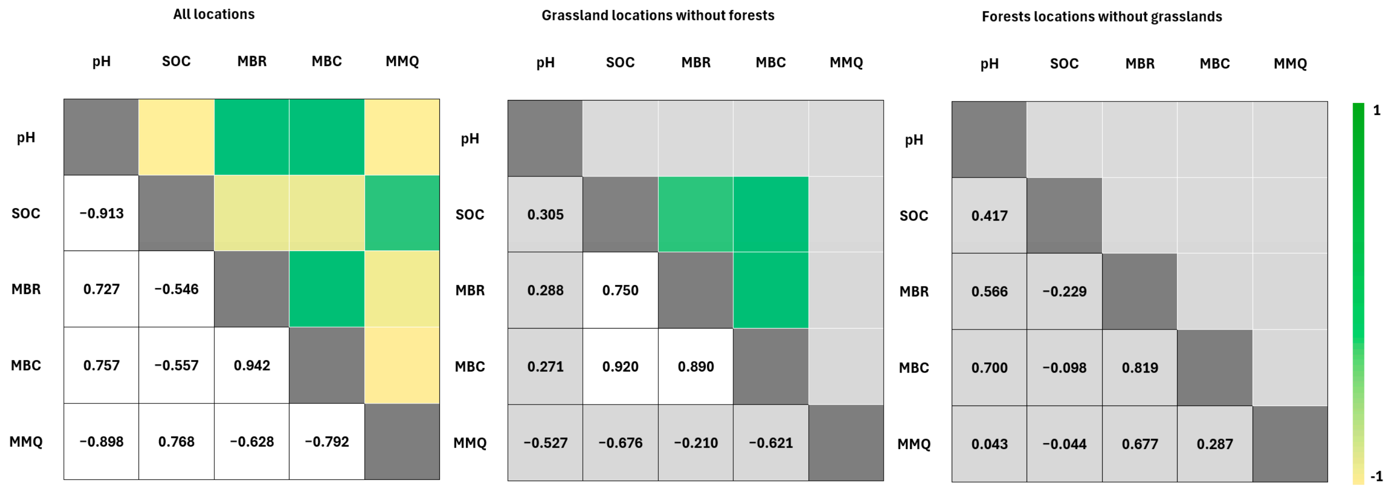

Figure 3. Correlation heat map for the evaluated parameters. Fields that are light grey were not evaluated due to statistical equality at all locations (*p*-value 0.05). Soil organic carbon (SOC), carbon of microbial biomass (MBC), microbial basal respiration (MBR), microbial metabolic quotient (MMQ).

3.3. Microbial Activity (MBR, MBC) as a Function of SOC

Soil microbial activity was measured using two basic indicators (MBR, MBC). The lowest MBR values were determined at both forest locations, which were also identical according to the statistical evaluation. The MBR values were higher for the grasslands. For MBC, the situation was similar to that of MBR. Lower MBC values were measured for forest locations compared to grasslands.

Based on the results (MBR, MBC), it was confirmed that microbial activity in soil differed between grasslands and forests (hypothesis 1), but statistical differences were also found for individual grassland locations (see, Table 3). In the case of MBR, only G2 and G3 were statistically identical. For MBC, no statistical concordance was confirmed and, therefore, each grassland location could be considered different.

The dependencies between MBR, MBC and SOC were assessed using the correlation coefficient and trend lines. When MBR and MBC were evaluated, there was a strong relationship (R^2 = 0.9461) between these two parameters. The dependence was confirmed when evaluating all locations, but only at grasslands (Figure 3). This points to the fact that different soil pH did not significantly affect this dependence. Thus, at the locations evaluated, it was valid that MBC increased with increasing MBR.

The above statement did not apply to the relationship between SOC and MBC. In assessing the correlation across all locations (Figure 3), an inverse correlation (−0.557) was found, but, when looking for a definite trend between SOC and MBC (Figure 4), it is clear that no trend (R^2 = 0.2914) was observed. The situation was completely different if the forest locations were omitted and only grassland locations with statistically equally high pH were evaluated. Then, a strong direct correlation (0.920) between SOC and MBC was evident and a significant trend (R^2 = 0.907) could be established (Figure 4).

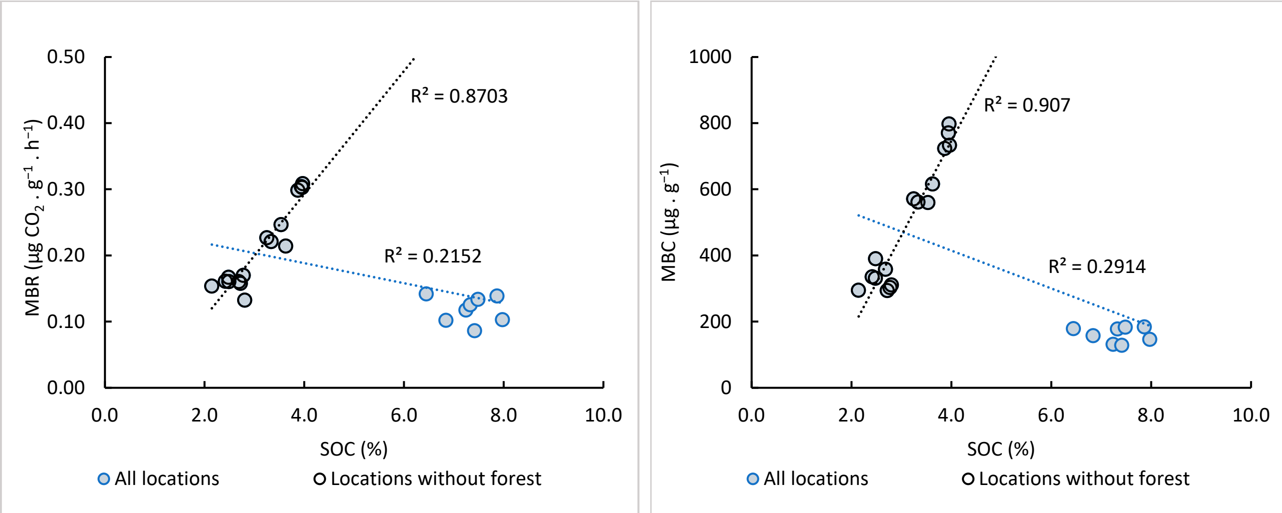

Figure 4. Relationship between SOC and microbial parameters. Soil organic carbon (SOC), carbon of microbial biomass (MBC), microbial basal respiration (MBR).

A similar situation, slightly less marked, existed for the relationship between SOC and MBR. When forest locations were included, an inverse correlation (−0.546) was found and the resulting trend (R^2 = 0.2152) was significantly negatively affected. When assessing only grassland locations, a strong direct correlation (0.750) was found and a significant trend (R^2 = 0.8703) was also established.

From the results, the conclusion was that hypothesis 2 (microbial activity assessed by MBR and MBC is SOC-dependent) was only valid for locations with the same pH. When different locations (grasslands and forests) were evaluated, the hypothesis was not confirmed.

In this paper, the efficiency of the microbial environment expressed in terms of MMQ was also calculated. The highest values were determined for forest locations, which were statistically significantly different from grasslands. It was also confirmed that all grasslands were statistically identical, as were forest locations (Table 3). Figure 3 shows that the highest correlation value (−0.898) was achieved between MMQ and pH when all locations were evaluated. Thus, the results indicate that the MMQ value increased with decreasing pH. An assessment of only grasslands or forests was not carried out for statistical concordance.

4. Discussion

Soil pH is one of the basic indicators that is monitored in a comprehensive soil assessment [50–52]. Its value influences a number of soil properties: physical, chemical and biological [53,54]. The level of pH is determined by the composition of the soil but is also influenced by the plants themselves, as the organic matter from each species can have significantly different compositions [55–57]. This can be clearly seen in Figure 2, where the pH at the two forest locations differed significantly from the pH at the grassland locations. The results confirm the generally accepted conclusion that coniferous forest locations need and have a lower pH than agricultural land in the upper soil layer (0–15 cm). This conclusion is in agreement with [58–60], but is only valid for topsoil, because at deeper soil levels, the differences in pH for individual land uses tend to decrease, as previously reported [61,62].

When assessing the pH of agricultural land, it must be taken into account that changes may occur as a result of agronomic operations. These may affect the pH. Some agrotechnical operations are directly carried out to adjust the pH to the optimum value for the crop [63]. The classic case is the liming of soils, which increases the pH [64]. However, the pH can also be lowered by, for example, applying certain types of mineral or organic fertilisers [65]. The way the soil is cultivated also has an influence. All these agrotechnical operations that are carried out affect not only pH but also other soil parameters including SOC, MBR and MBC [66,67]. The greatest changes in soil parameters can be expected on arable land, where the soil is generally subjected to more frequent cultivation than grasslands and forests. In this context, it is important to note that no agrotechnical operations (liming, organic fertilisation) were carried out on the experimental locations during the research that would have significantly altered the pH. This is apparent from Table 2 (standard deviation) and Figure 2 (box plots).

Similar to pH, the amount of SOC is influenced by a number of parameters. Some of the basic ones include the type of farming [68], soil texture [69] or species composition [70]. In evaluating the relationship of SOC with other parameters, certain dependencies were found. A very strong correlation was determined between pH and SOC, but it must be added that the results were valid for the upper layer in which the sampling took place (0–15 cm). For deeper soil levels, this statement may not be valid. This was also confirmed by some studies in which sampling was carried out in lower layers [43]. The same relationship (ph–SOC) in upper layer was found by [71] in a tropical forest soil environment, [72] in grasslands and forests, and [59] in steppe and cropland locations. Based on the results (Table 2), it can be confirmed with some simplification that, in this case, higher SOC was measured in forest locations due to a more acidic soil environment. This conclusion is also clearly visible in Figure 3, which shows the correlation coefficient between the evaluated parameters. For higher pH (above 8), this may no longer be applicable, as [73] reported a hump-back model between soil organic carbon and pH in grasslands. On arable land, there may even be reverse dependence due to soil cultivation, as noted by [74], i.e., a decrease in organic carbon as pH decreases. This means that hypothesis 3 involving the dependence of SOC on pH was only partially confirmed because in significantly different soil environments than those in this study, the relationship may not always be valid. This observed pH–SOC relationship can be significantly disturbed by agrotechnical operations. It is therefore essential to know the management practices that have been applied to the land.

There were also some findings for SOC and microbial activity (MBR, MBC). In the case of MBC, the lowest values were found at forest locations (F1, F2). The values in this study are in agreement with many authors [75–77] who determined the MBC for forest soils. However, values at forest locations can vary considerably. The main reason is due to the complicated soil sampling. It is necessary to separate soil from forest floor during sampling because [78,79] reported that MBC can vary significantly between forest floor and forest soil. For grassland, some authors [80,81] gave similar values to those in this paper, but, in some studies [82,83], there were higher values.

The situation was similar for MBR, but not the same. Almost all locations were statistically different, but several individual MBR values from forest locations were comparable to those of some grassland locations (Figure 4). This finding is in agreement with [84], who also compared grasslands and forests. When evaluating the relationship between MBR and MBC, it can be concluded that a higher MBR in soil indicates a higher MBC (Figure 5), as confirmed by other authors [85,86].

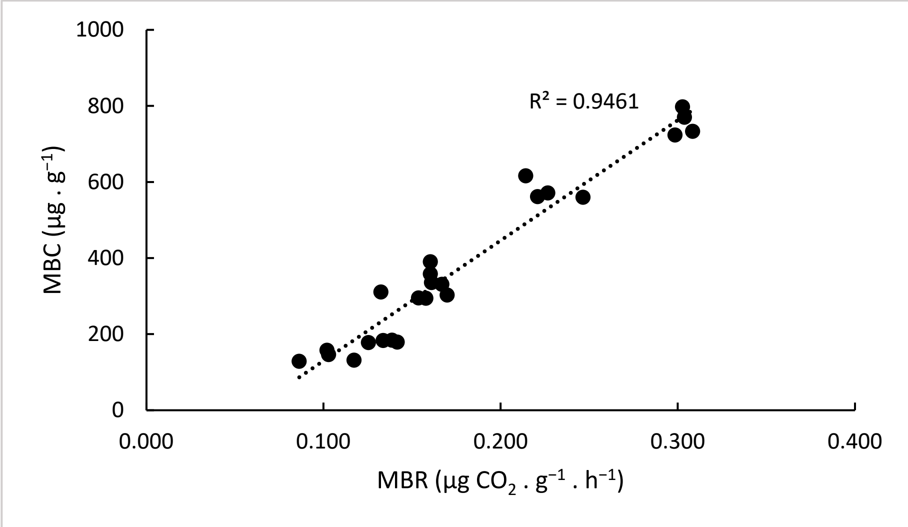

Figure 5. Dependence between basic parameters related to microbial activity (MBR, MBC). Carbon of microbial biomass (MBC), microbial basal respiration (MBR).

From the results of the SOC–MBC and SOC–MBR relationships, it can be further assumed that the more SOC in the soil, the more microorganisms. This is in line with other authors [87–89], but only applicable when the pH is the same. When forest locations are included, this statement cannot be confirmed. The same conclusion may apply to the MBR. A strong correlation between SOC and MBR at grassland locations was reported by [90,91] and also by [92], who assessed only forest locations.

MMQ is considered an important indicator of soil health [93] and the highest correlation was found for pH. Similar findings were reported in a study by [94], who analysed 24 studies and concluded that MMQ often declines with increasing pH in a stable environment. The results indicate that organic matter is more efficiently used by microorganisms in grassland locations, where MMQ is lower compared to forest locations. Higher ratios may reflect that the microbial community is exposed to stressful conditions such as inappropriate pH (Table 2). This means that microorganisms must expend more energy to maintain basic life functions and use less for growth [95]. Soil pH is not the only parameter that affects MMQ, but there are other soil parameters such as clay content, amount of MBC [94] or soil moisture [96].

The conclusion regarding the relationship between SOC and MBC, SOC and MBR or pH and MMQ highlights the issue of overgeneralisation. In some cases, it is not possible to make general conclusions that apply across locations. This is also the case for microbial activity, which is influenced by a number of factors. These factors may vary due to different land cover types and it is therefore always important to take into account basic parameters (e.g., pH) that may differ between land use types.

5. Conclusions

This paper summarised the knowledge concerning organic matter and its microbial role. The results show that some significant trends and dependencies can be found for the parameters evaluated (SOC, MBR, MBC). When assessing microbial activity, both parameters MBR and MBC appear to be suitable indicators in relation to SOC. However, it is also important to assess other parameters such as the pH in the soil environment. Different pH levels can significantly affect the resulting trends, which was evident when forest locations were included. The findings support the current knowledge of soil organic matter and are useful for other authors in evaluating and interpreting results related to microbial activity. Information on microbial activity is also important from the point of view of soil quality. This can be influenced (both negatively and positively) in the long term by the way it is managed. Therefore, management practices that contribute to the enrichment of the diversity of microflora and microfauna in the ecosystem should be promoted in order to increase landscape stability and improve soil health, crop health and agricultural production. From this perspective, it would be interesting to better clarify the dynamics of pH, SOC, MBR and MBC in other ecological systems and land use types. Microbial activity through the decomposition of organic matter influences nutrient cycles, and a deeper understanding of this could provide more support for sustainable management practices and development.

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4.8 Materiály z aplikovaného výzkumu týkající se ochrany půdy

Tato kapitola obsahuje informace o vybraných dosažených aplikovaných materiálech definovaných dle VaVaI (Rejstřík informací o výsledcích – RIV, 2026), které tematicky přímo souvisí s obsahem habilitační práce. Uvedené jsou výsledek typu B (monografie) a dále pak výsledky N_{met} (certifikované metodiky). Nejedná se tak o všechny dosažené výsledky. Aplikované materiály jsou velmi důležité pro přenos získaných poznatků do praxe. Zpravidla přinášejí různá doporučení, technologické postupy, metodické návody či inovativní řešení. Díky nim lze optimalizovat způsob hospodaření a zvýšit jeho efektivitu.

Přehled aplikovaných výsledků je uveden níže. Každý výsledek je popsán formou citace, abstraktu (či cíle) a je doplň úvodní stranou a stranou s uvedenými autory. Plné znění dosaženého výsledku je k dispozici v knihovně příslušné organizace podílející se na vydání. Některé z výsledků jsou dostupné rovněž v online verzi.

Monografie:

1. Menšík, L., Kincl, D., Nerušil, P., Srbek, J., **Kabelka, D.**, Herout, M., Jurka, M., Šedek, A., Horký, T., Vach, M. (2018). *Pěstování kukuřice seté půdoochrannými technologiemi. Příkladová studie Boskovická brázda a Středočeská pahorkatina*. Výzkumný ústav rostlinné výroby, v. v. i. a Výzkumný ústav meliorací a ochrany půdy, v. v. i., Praha, s. 102.

Abstrakt

Studie předkládá výsledky výzkumného projektu „Komplexní půdoochranné technologie zakládání *Zea mays* L. v rámci reintenzifikace rostlinné výroby“ řešeného na pracovištích VÚMOP, v. v. i.; VÚRV, v. v. i.; P & L spol. s. r. o.; ZD Krásná Hora nad Vltavou a. s. a Hanácká zemědělská společnost Jevíčko a. s. v letech 2015-2018. Projekt byl finančně podpořen MZe ČR. Případová studie z oblasti Boskovické brázdy a Středočeské pahorkatiny je příspěvkem ke zdůvodnění smysluplnosti, ekologického i ekonomického přínosu pěstování kukuřice půdoochrannými technologiemi pro fungování agroekosystémů v současných měnících se podmínkách prostředí (předpokládaná změna klimatu) zemědělské výroby v České republice. Design experimentu se sestával z variant půdoochranných technologií (pásové zpracování půdy / strip-till - jarní, podzimní u porostu žita setého, resp. travního porostu na orné půdě / a přímé setí / široký a úzký řádek do strniště, resp. porostu žita setého) a varianty konvenční (orba), které byly testovány v maloparcelových podmínkách a poloprovozních experimentálních plochách ve dvou odlišných půdně-klimatických podmínkách.

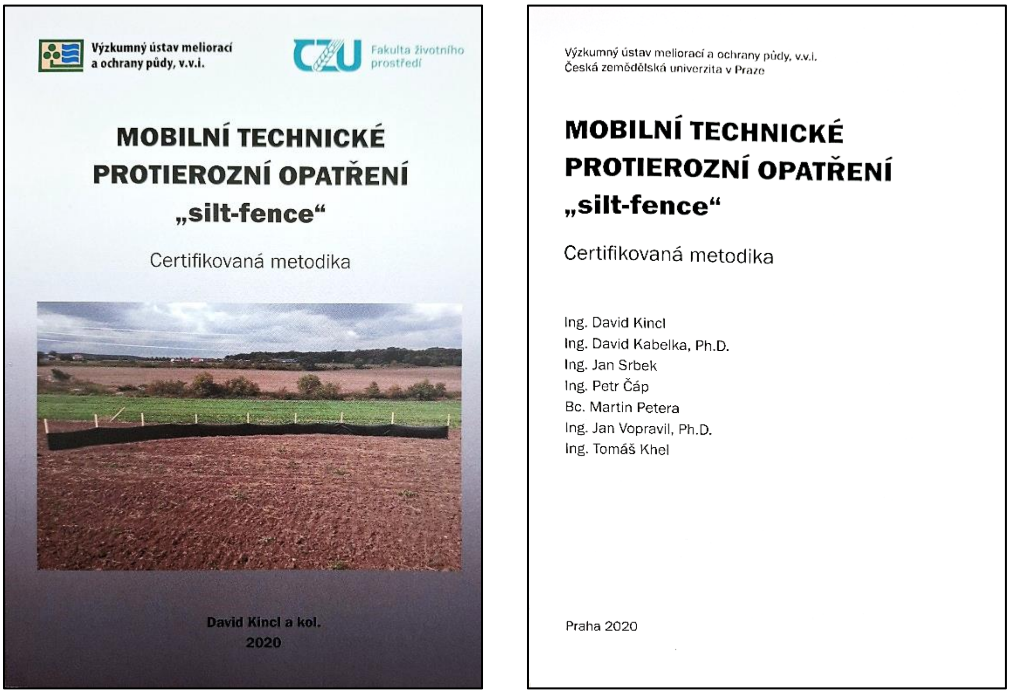
Obrázek 2: Monografie věnující se problematice půdoochranných technologií při pěstování kukuřice seté.

Certifikovaná metodika (N_{met})

1. Kincl, D., **Kabelka, D.**, Srbek, J., Čáp, P., Petera, M., Vopravil, J., Khel, T. (2020). *Mobilní technické protierozní opatření „silt-fence“*. Certifikovaná metodika, Výzkumný ústav meliorací a ochrany půdy, v. v. i., Praha, s. 41.

Abstrakt

Certifikovaná metodika pojednává o možnostech a podmínkách využití protierozní textilie silt-fence pro co nejúčinnější omezení vodní eroze. Podrobně jsou zmiňovány používané materiály a jejich technické parametry, prostředky využívané pro instalaci, údržba opatření, způsoby a moznosti instalace. Metodika dále uvádí i výsledky zkušenosti z ověřování v našich podmínkách. Tyto pokusy byly opakovaně prováděny v simulovaných i poloprovozních podmínkách. Výsledky poukazují na vysokou účinnost zachycení erodované půdy a poměrně spolehlivé rozdělení mikropovodí a směřování povrchového odtoku do požadovaného místa. V závěru metodiky jsou vyjádřeny finanční náklady na realizaci i odstranění protierozní textilie silt-fence. Tyto náklady byly kalkulovány vzhledem k současně dostupné technice na našem trhu a standardním cenám stavebních a zemních prací. Hlavním záměrem této metodiky je zavést protierozní textilii silt-fence do běžné práce v rámci ČR a nabídnout odborné veřejnosti další možnost, jak omezit vodní erozi.



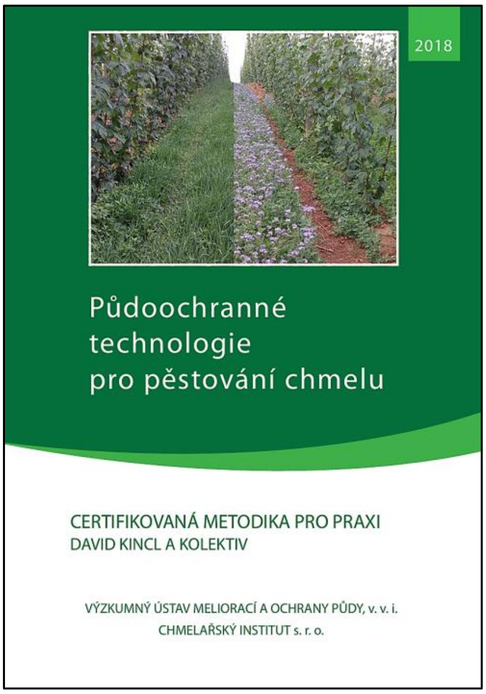
Obrázek 3: Certifikovaná metodika zaměřená na mobilní technická protierozní opatření.

Certifikovaná metodika (N_{met})

2. Kincl, D., **Kabelka, D.**, Srbek, J., Čáp, P., Petrů, A., Petera, M., Krofta, K., Pokorný, J. (2018). *Půdoochranné technologie pro pěstování chmelu*. Certifikovaná metodika, Výzkumný ústav meliorací a ochrany půdy, v. v. i., Praha, s. 23.

Abstrakt

Pěstování chmele má tisíciletou tradici. České chmelnice si za tuto dobu vytvořily nejen u nás, ale i ve světě své výsadní postavení. V současné době bohužel není v našich podmínkách při obhospodařování chmele otáčivého (*Humulus lupulus* L.) prováděna žádná systematická ochrana zabraňující erozi půdy. Na erozně ohrožených chmelnicích každoročně vlivem silných dešťů dochází k nenávratným ztrátám půdy a živin, což vede k postupnému snižování úrodnosti. Splavená půda navíc způsobuje řadu problémů v podobě zanášení vodních toků, znečištění komunikací či v horším případě poškození majetku. Tento stav není dlouhodobě udržitelný, a proto je potřeba provádět příslušná opatření sloužící k ochraně erozně ohrožených chmelnic. Jednou z možností, jak omezit vodní erozi na chmelnicích a ochránit tím svažité pozemky, je využití vhodně zvolených meziplodin v meziřadí. V certifikované metodice jsou představeny půdoochranné technologie postavené na třech základních principech: nízké ekonomické náklady, neovlivněná produkce chmele a dostatečná protierozní ochrana půdy.




Metodika byla vytvořena jako výstup pro praxi v rámci projektu NAZV QJ1610418 „Komplexní půdoochranné technologie pro pěstování chmelu otáčivého" a s finanční podporou MZE-RO0218. Zvláštní poděkování pak patří panu Ing. Jiřímu Helebrantovi z firmy Chmel Helebrant s. r. o. za vstřícnost během provádění experimentů na chmelnicích v Solopyskách (okr. Louny).

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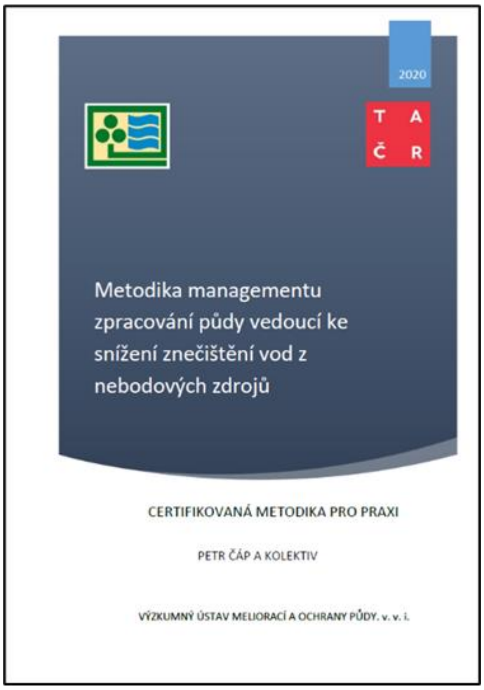
Obrázek 4: Certifikovaná metodika zaměřená na využití meziplodin ve chmelnicích.

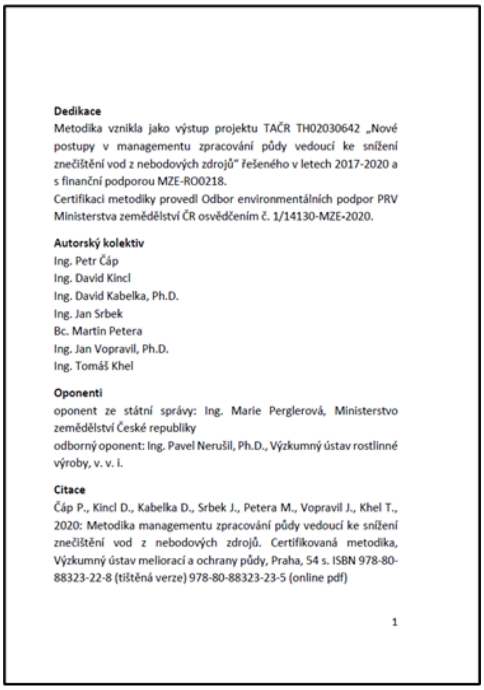
Certifikovaná metodika (N_{met})

3. Čáp, P., Kincl, D., **Kabelka, D.**, Srbek, J., Petera, M., Vopravil, J., Khel, T. (2020). *Metodika managementu zpracování půdy vedoucí ke snížení znečištění vod z nebodových zdrojů*. Certifikovaná metodika, Výzkumný ústav meliorací a ochrany půdy, v. v. i., Praha, s. 54.

Abstrakt

Cílem metodiky je upozornit na negativní vliv vodní eroze, která vzniká v důsledku přirozených srážek na plochách s kukuřicí setou. Konkrétně na odnos živin obsažených v erodovaném materiálu a v povrchovém odtoku. V České republice nebyla doposud věnována dostatečná pozornost zhodnocení půdoochranných technologií z pohledu jejich vlivu na snížení odnosu živin a finančnímu vyhodnocení těchto technologií z pohledu nákladů potřebných k nahrazení ztráty živin vyplavených vlivem vodní eroze. Z tohoto důvodu vznikla tato metodika, která si klade za cíl kvantifikovat ztrátu živin působením vodní eroze při použití různých systémů pěstování kukuřice seté a podat tak nejen zemědělským subjektům informace, jaký vliv má využití půdoochranných technologií z pohledu snížení ztráty přístupných živin v důsledku erozního procesu. Metodika rovněž předkládá ucelený návod pro ekonomické vyhodnocení nákladů potřebných pro nákup hnojiv, která jsou nutná k nahrazení odplavených živin a nabízí porovnání účinnosti půdoochranných technologií vzhledem ke konvenčnímu způsobu pěstování kukuřice.





Dedikace

Metodika vznikla jako výstup projektu TAČR TH02030642 „Nové postupy v managementu zpracování půdy vedoucí ke snížení znečištění vod z nebodových zdrojů" řešeného v letech 2017-2020 a s finanční podporou MZE-RO0218.
Certifikaci metodiky provedl Odbor environmentálních podpor PRV Ministerstva zemědělství ČR osvědčením č. 1/14130-MZE-2020.

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odborný oponent: Ing. Pavel Nerušil, Ph.D., Výzkumný ústav rostlinné výroby, v. v. i.

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1

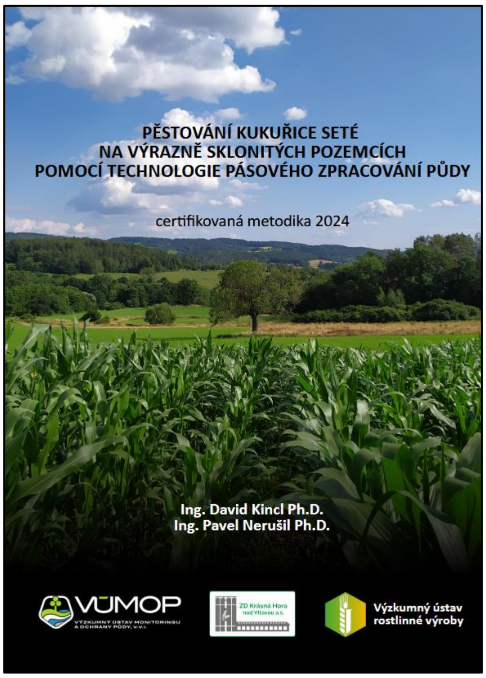
Obrázek 5: Certifikovaná metodika věnující se problematice znečištění vod z nebodových zdrojů.

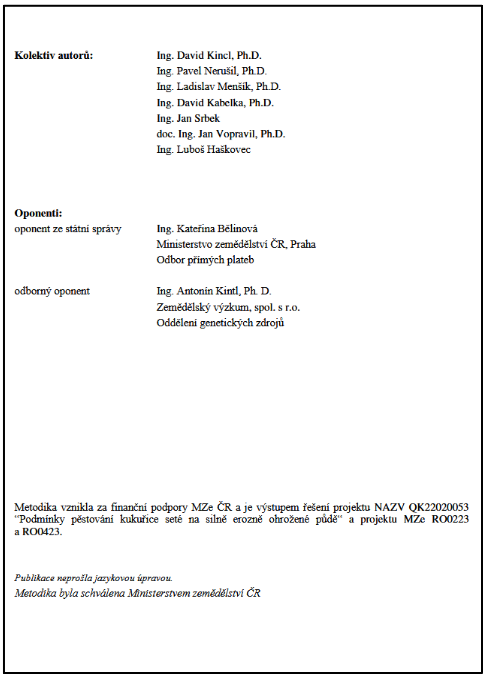
Certifikovaná metodika (N_{met})

4. Kincl, D., Nerušil, P., Menšík, L., **Kabelka, D.**, Srbek, J., Vopravil, J., Haškovec, L. (2024). *Pěstování kukuřice seté na výrazně sklonitých pozemcích pomocí technologie pásového zpracování půdy*. Certifikovaná metodika, Výzkumný ústav meliorací a ochrany půdy, v. v. i., Praha, s. 50.

Abstrakt

Certifikovaná metodika je dílčím výstupem projektu Národní agentury pro zemědělský výzkum (NAZV) „Podmínky pěstování kukuřice seté na silně erozně ohrožené půdě" a poskytuje nové poznatky o možnostech využití půdoochranné technologie pásového zpracování půdy (strip-till) na výrazně sklonitých pozemcích. Pěstování kukuřice seté s využitím pásového zpracování půdy nabízí nový technologický způsob, jak využít méně hodnotné travní porosty na orné půdě, u kterých musí být provedena pěstební obnova. Na rozdíl od klasické technologie se pozemek zpracuje pouze pásově (s šíří pásku cca 0,15 m) na obvyklou rozteč 0,75 m pro širokořádkové plodiny. Nezpracovaná část umrtveného travního porostu má funkci chránit půdu a zpomalovat povrchový odtok tak, aby voda měla delší čas zasáknout. Tento efekt je možné pozorovat prakticky po celé období růstu kukuřice, kdy se výrazně minimalizuje možnost vzniku vodní eroze. Účinnost technologie je tak výrazná, že tento postup umožňuje pěstovat kukuřici setou i na silně erozně ohrožené půdě. Prozatím je ovšem zařazení této technologie do standardů DZES 5 v přípravě s Ministerstvem zemědělství. Představovaný technologický postup proto zemědělcům nabízí další možnost, jak zásadně omezit ztrátu půdy pro zpravidla jednu z nejvíce erozně náchylných plodin v jejich osevním postupu.





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odborný oponent: Ing. Antonín Kintl, Ph. D., Zemědělský výzkum, spol. s r.o., Oddělení genetických zdrojů

Metodika vznikla za finanční podpory MZe ČR a je výstupem řešení projektu NAZV QK22020053 "Podmínky pěstování kukuřice seté na silně erozně ohrožené půdě" a projektu MZe RO0223 a RO0423.

Publikace neprošla jazykovou úpravou.
Metodika byla schválena Ministerstvem zemědělství ČR

Obrázek 6: Certifikovaná metodika zaměřená na vysoce účinné půdoochranné technologie pro kukuřici setou.

Certifikovaná metodika (N_{met})

5. Vopravil, J., Brant, V., Koulík, M., **Kabelka, D.**, Krofta, K., Dreksler, J., Procházka, P., Kincl, D., Zábranský, P. (2022). *Optimalizace zpracování půdy ve chmelnicích za účelem podpory infiltrace vody a ochrany půdy před degradačními procesy*. Certifikovaná metodika, Výzkumný ústav meliorací a ochrany půdy, v. v. i. a Česká zemědělská univerzita v Praze, Praha, s. 90.

Abstrakt

Cílem metodiky je poskytnout ucelený návod a představit dosavadní poznatky týkající se hospodaření ve chmelnicích s využitím meziplodin v meziřadí. Zvláštní pozornost je věnována možnostem zpracování půdy v případě ozelenění meziřadí a dále pak způsobům zakládání porostů meziplodin. Optimalizace stávajících a zavádění nových technologických postupů vyžaduje i dostupnost vhodné agrotechniky. Proto je část metodiky věnována agrotechnickým prostředkům, pomocí kterých je možné úspěšně uplatňovat nově představené technologie zpracování půdy v meziřadí. Technologie založené na principech biologického zpracování půdy uvedené v metodice patří mezi tzv. půdoochranné. V důsledku jejich využívání dochází ke snižování rozsahu degradačních procesů ve srovnání s klasickými postupy obhospodařování chmelnic, které se do budoucna jeví jako neudržitelné.

Obrázek 7: Certifikovaná metodika zaměřená na cílené zpracování půdy v prostoru meziřadí chmelnic.

5 Zhodnocení výsledků pro další rozvoj vědecké disciplíny

Z vědeckého hlediska habilitační práce rozšiřuje poznání primárně v oblasti ochrany půdy před vodní erozí. Poznatky jsou však uplatnitelné také v dalších souvisejících vědních disciplínách, jako jsou hydrologie, krajinná ekologie či udržitelný rozvoj. Uvedené výsledky přináší v řadě případů jedinečné informace o protierozní účinnosti agrotechnických způsobů pěstování vybraných erozně náchylných plodin v podmínkách České republiky.

Každá z publikací obsahuje metodický postup, pomocí kterého byly poznatky získány. Přínos práce lze v tomto kontextu chápat jako určitý návod pro ostatní vědecké pracovníky, kteří se zabývají či mají zájem se zabývat protierozní ochranou. Z uvedených informací mohou načerpat inspiraci a pokračovat v získávání nových poznatků spojených s protierozní ochranou a souvisejícími vědními obory.

Výsledky mají rovněž potenciál rozvíjet vědní obory v podobě vstupních dat. V dnešní době existuje mnoho modelů, na základě kterých, je možné provádět modelování přírodních procesů. Pro vytvoření maximální přesnosti je nezbytné mít k dispozici kvalitní vstupní data. Parametr týkající se kvality vstupních dat, výsledky v uvedených publikacích splňují. V případě vědeckých článků, kde je využit polní simulátor deště, se jedná vždy o opakovaná a víceletá měření. I u zbývajících publikací byl kladen důraz, aby měření proběhla v dostatečném opakování. Cílem bylo získat informace vytvořené na dostatečně silném základu. Níže jsou uvedeny případy, kde je možné s výsledky dále pracovat a rozvíjet současné vědecké poznání (lze to chápat také jako další využití v praxi, viz následující kapitola):

- **Stanovení ochranného vlivu vegetace (C-faktor) a erodovatelnosti půdy (K-faktor)**. Jedná se vstupní parametry do celosvětově využívaných rovnic: Univerzální rovnice ztráty půdy USLE (*Universal Soil Loss Equation*) využívaná pro výpočet dlouhodobé ztráty půdy, případně Revidovaná univerzální rovnice ztráty půdy RUSLE (*Revised Universal Soil Loss Equation*).
- **Modelace množství odtoku vody pomocí CN křivek (SCS Curve Number).**
- **Oblast hydrologie**: infiltrační kapacita půdy, Manningův koeficient drsnosti.
- **Modelace založené na specializovaných softwarech.**
- **aj.**

6 Zhodnocení výsledků pro využití v praxi

Praktický přínos spočívá v ověření protierozní účinnosti konkrétních půdoochranných technologií u významných plodin. Výsledky mají informativní účel a slouží jako doplňující odborný podklad prohlubující znalost o půdoochranných postupech hospodaření. Pro využití v praxi jsou klíčové materiály uvedené v kapitole 4.8. Ta je zaměřena na aplikované výsledky (monografie, certifikované metodiky). Metodické návody jsou vytvářeny přímo pro zemědělské subjekty. Díky nim uživatelé metodik zjistí dodatečné informace a lépe tak zvládnout zařaření půdoochranné technologie do svých agrotechnických postupů. Vědecké články lze v této souvislosti chápat jako další zdroj důležitých informací, který nemusí být v metodických návodech vždy uvedeny.

Výsledky jsou dále vhodné pro poradenské organizace či pro státní sféru. U poradenství se jedná o využití při různých školeních, odborných seminářích či workshopech. V případě státní sféry mohou být výsledky využity jako podpůrný materiál při rozhodování o zavedení nových opatření. Vzhledem k tematickému zaměření habilitační práce jsou výsledky přímo využitelné pro nastavovní standardů Dobrého zemědělského a environmentálního stavu půdy, tzv. DZES (dříve GAEC). Půdoochranným technologiím se věnuje konkrétně DZES 5 (platné pro rok 2026), jehož cílem je ochrana půdy před vodní erozí a současně také snaha o předcházní důsledků eroze. Protierozní ochrana je v DZES 5 řešena stanovením požadavků na technologický způsob pěstování hlavních plodin na svažitých pozemcích. Jedním z požadavků může být pěstování erozně náchylné plodiny (např. kukuřice) pouze s využitím půdoochranné technologie. Při nastavování požadavků je důležité mít k dispozici data, která dokážou daný požadavek vědecky podpořit a obhájit. Řada informací v habilitační práci vznikla cíleně pro tento účel.

Vědecké články vznikají často jako dílčí část projektové činnosti. Díky projektům je možné řešenou problematiku popsat v širším kontextu. Ne jinak tomu bylo v případě této habilitační práce. Seznam klíčových projektů je uveden v kapitole 8. Poznatky získané z dalších oblastí, kterým se projekty věnují, dále prohlubují znalosti. I díky takto komplexně pojatému ověření je možné v dnešní době půdoochranné technologie vidět běžně v praxi.

V neposlední řadě jsou výsledky určené pro využití v univerzitním prostředí při výuce vysokoškolských studentů. Teoretický základ doplněný o reálné poznatky z výzkumu lépe dokresluje danou problematiku, v tomto případě půdoochranné technologie a jejich protierozní účinnost. U univerzit, jako je Jihočeská univerzita v Českých Budějovicích – Fakulta zemědělská a technologická, mohou poznatky z výzkumu pomoci s častějším uplatňováním půdoochranných technologií. Řada studentů se zabývá hospodařením na zemědělské půdě již při studiu či plánují tuto činnost provádět po skončení studia. Nově získané poznatky jsou tímto způsobem dále šířeny a uplatňovány.

7 Teoretický a společenský přínos

Teoretický přínos spočívá v podrobném popisu problematiky půdoochranných technologií z pohledu vodní eroze založeném na odborně zpracovaných datech. Habilitační práce systematicky propojuje poznatky o půdním prostředí, degradačních procesech a agrotechnických způsobech hospodaření v úvodní části, po které následuje část skládající se z odborných publikací. Díky tomu vznikl ucelený soubor informací o udržitelném způsobu hospodaření. Práce zdůrazňuje skutečnost, že v případě půdy se jedná o komplexní přírodní ekosystém zajišťující mnoho mimoprodukčních funkcí, které by měly být podporovány.

Společenský přínos práce lze chápat v kontextu aktuálních výzev, kterým čelí zemědělství i společnost jako celek. Mezi tyto výzvy patří klimatická změna, vysoký stupeň degradace půdního fondu či tlak na produkci potravin při současném požadavku na ochranu životního prostředí. Častější využívání půdoochranných technologií má silný potenciál pozitivně ovlivnit všechny výše uvedené výzvy. Informace uvedené v práci rovněž vytváří odborně podložený základ pro případnou diskusi o budoucím vývoji zemědělství v kontextu udržitelného rozvoje.

8 Projekty, s jejichž podporou byla práce zpracována

V této kapitole jsou uvedeny klíčové projekty, pomocí kterých byly vytvořeny vědecké publikace a aplikované výsledky.

Projekty NAZV a TAČR

1. NAZV QK21010161: Význam lignocelulózového komplexu z biomasy meziplodin pro zlepšení půdního prostředí, doba řešení 2021 – 2025.
2. NAZV QK22020053: Podmínky pěstování kukuřice seté na silně erozně ohrožené půdě, doba řešení 2022 – 2024.
3. NAZV QK21020069: Korekce hodnot erodovatelnosti půdy dle morfologie terénu v rámci erozně uzavřených celků pro potřeby zpřesnění identifikace erozně ohrožených ploch, doba řešení 2021 – 2023.
4. NAZV QK1910170: Zajištění dlouhodobé konkurenceschopnosti českého chmelařství na základě implementace principů precizního zemědělství a technologií smart farming, doba řešení 2019 – 2023.
5. NAZV QK1910334: Inovace šetrných systémů pěstování kukuřice s využitím podsevových plodin k omezení degradace půdy a zlepšení hospodaření s vodou v podmínkách měnícího se klimatu, doba řešení 2019 – 2023.
6. NAZV QK1710242: Mobilní technická protierozní opatření pro pěstování kukuřice, doba řešení 2017 – 2021.
7. TAČR TH02030642: Nové postupy v managementu zpracování půdy vedoucí k snížení znečištění vod z nebodových zdrojů, doba řešení 2017 – 2020.
8. NAZV QJ1610418: Komplexní půdoochranné technologie pro pěstování chmele otáčivého, doba řešení 2016 – 2018.
9. NAZV QJ1510179: Komplexní půdoochranné technologie zakládání *Zea mays* L. v rámci reintenzifikace rostlinné výroby, doba řešení 2015 – 2018.

Institucionální podpora od MZe

1. Institucionální podpora záměru MZE-RO0218 (VÚMOP).
2. Institucionální podpora záměru MZE-RO0223 (VÚMOP).

Při tvorbě vědeckých publikací byly využity některé další granty, které jsou vždy uvedeny u dané publikace.

Závěr

Problematika ochrany půdy před degradačními procesy je dlouhodobě aktuálním tématem zasahujícím do celého světa. Vzhledem k neustále se měnícím podmínkám pro hospodaření na zemědělské půdě je důležité poskytnout zemědělským subjektům dostatek vhodných a řádně ověřených způsobů hospodaření. Faktem ale zůstává, že cílem hospodaření by mělo být dosažení zisku při zachování zodpovědného využívání přírodních zdrojů. Jestliže je snaha omezovat degradační procesy a postupně vracet degradované půdě její základní vlastnosti, je nezbytné půdoochranné technologie využívat.

Předmětem habilitační práce není kritika konvenčních agrotechnických postupů, ale snaha poukázat na některé výhody půdoochranných technologií, které představují určitou alternativu právě ke konvenčním postupům. Ne vždy lze daný typ půdoochranné technologie úspěšně využít na všech pozemcích. Proto by měla být možnost volby mezi různými agrotechnickými postupy. Tento princip v České republice v zásadě funguje a zemědělský subjekt má dnes možnost vybrat si takový způsob zpracování půdy, který bude nejvíce vhodný pro jeho pozemek a technické možnosti. Určitou výjimkou jsou rizikové pozemky, kde je zemědělský subjekt omezen různými legislativními opatřeními.

Pokud mají být půdoochranné technologie základem při omezování vodní eroze, je nezbytné, aby byla známa jejich protierozní účinnost, výnosovost a ekonomická náročnost. Informace o uvedených ukazatelích následně slouží jako základní argumentační podklad a odůvodnění při jejich zavádění. Stejně tak ale mohou tyto informace přispět zemědělskému subjektu při rozhodování o výběru agrotechnického způsobu hospodaření.

Habilitační práce obsahuje celou řadu informací o protierozní účinnosti agrotechnických postupů u vybraných plodin. Ty jsou doplněny o související informace, které se zabývají povrchovým odtokem a organickou hmotou. Jednotlivé publikace vznikaly většinově v rámci komplexní výzkumné činnosti (projektů), kde docházelo k ověřování dalších výše zmíněných parametrů (ekonomická náročnost, výnosovost). Proto lze hodnocené agrotechnické postupy považovat za řádně ověřené. Půdu máme jenom jednu, a je potřeba mít na paměti, že pokud si ji jednou zničíme, její náprava je velice obtížná a v některých případech i těžce realizovatelná.

Summary

The issue of soil conservation against degradation processes has long been a global problem. If the aim is to reduce the range of degradation processes and gradually restore the basic properties of degraded soil, it is essential to use sustainable management practices. In this context, it is important to provide farmers a sufficient number of proven agrotechnical methods.

Knowledge in the area of agriculture is rapidly expanding. As a result, a wide range of specialized materials is available. These demonstrate that it is possible to effectively use agrotechnical methods that differ from conventional ones during crop cultivation. Under certain conditions, alternative agrotechnical methods can be more economical than conventional approaches (fewer passes over the land, targeted and variable application of fertilizers etc.). In connection with the problem of water erosion, agrotechnical methods are referred to as soil conservation technologies (or techniques). Soil conservation technologies for plants that are prone to erosion are the main topic of this habilitation thesis. It consists from individual scientific publications focused on the issue of soil degradation and the effectiveness of soil conservation technologies in terms of water erosion and surface runoff.

For the successful implementation of soil conservation technologies in practice, it is necessary to know their effectiveness against erosion, level of yield, and economic demands. Knowledge of these indicators then serves as a basis for argumentation and justification of their application. Similarly, this information can also help farmers in deciding which agrotechnical methods to choose.

The habilitation thesis contains a wide range of results about the soil erosion control effectiveness of agrotechnical methods for selected crops. These are supplemented by related chapters dealing with surface runoff and organic matter. Most of the individual scientific publications were created as part of comprehensive research activities (projects) where the other parameters mentioned above (yield production, economic demands) were verified. Therefore, the evaluated agrotechnical methods can be considered sufficiently verified. When farming, it is important to remember that once soil is destroyed, it is very difficult to restore, and in some cases almost impossible.

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