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mgr inż. Sebastian Kuśmierz

Rozprawa doktorska

Aspekty środowiskowe obecności związków węgla i azotu w gospodarstwach rolnych

Environmental aspects of the presence of carbon and nitrogen compounds in farms

Rozprawa doktorska wykonana w Katedrze Chemii Rolnej i Środowiskowej
Promotor: dr hab. Monika Skowrońska, profesor uczelni

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P.1. **Kuśmierz S.,** Skowrońska, M., Tkaczyk P., Lipiński W., Mielniczuk J. 2023. Soil organic carbon and mineral nitrogen contents in soils as affected by their pH, texture and fertilization. Agronomy 2023, 13, 267. https://doi.org/10.3390/agronomy13010267

MEiN 100 pkt, IF = 3,7

Mój wkład w powstanie tej pracy polegał na udziale w opracowaniu koncepcji badań, zaplanowaniu i przeprowadzeniu badań naukowych, analizie wyników, przygotowaniu i redagowaniu manuskryptu. Mój udział szacuję na 55%.

P.2. Skowrońska M., **Kuśmierz S.**, Walczak J. 2024. Selected carbon and nitrogen compounds in a maize agroecosystem under the use of nitrogen mineral fertilizer, farmyard manure, urease, and nitrification inhibitors. Agriculture 14, 274. https://doi.org/10.3390/agriculture14020274

MEiN 100 pkt, IF = 3,6

Mój wkład w powstanie tej pracy polegał na udziale w opracowaniu koncepcji badań, zaplanowaniu i przeprowadzeniu badań naukowych, analizie wyników, przygotowaniu i redagowaniu manuskryptu. Mój udział szacuję na 40%.

P.3. **Kuśmierz S.**, Skowrońska M. 2024. Carbon farming and nutrient management: influential factors of Polish farmers' perception of pro-climate measures. Agronomy Science 1, 79, online first, 1–13. https://doi.org/10.24326/as.2024.5324

MEiN 70 pkt

Mój wkład w powstanie tej pracy polegał na udziale w opracowaniu koncepcji badań, zaplanowaniu i przeprowadzeniu badań naukowych, ankietowaniu respondentów, analizie wyników, przygotowaniu i redagowaniu manuskryptu. Mój udział szacuję na 90%.

SPIS TREŚCI

Streszczenie

Aspekty środowiskowe obecności związków węgla i azotu w gospodarstwach rolnych

Zastosowanie odpowiednich praktyk w gospodarstwach rolnych pozwala na utrzymanie optymalnych zawartości związków węgla i azotu w glebach oraz ograniczenie ich rozpraszania w środowisku. Celami badań były: a) identyfikacja skutecznych praktyk nawozowych stosowanych w gospodarstwach rolnych, które wpływają na akumulację węgla organicznego i azotu mineralnego w polskich warunkach środowiskowych, b) określenie oddziaływania wybranych praktyk nawozowych na zmiany ilościowe i jakościowe związków węgla i azotu w agroekosystemie, c) ocena wdrażania praktyk ograniczających negatywny wpływ produkcji roślinnej na obieg węgla i azotu oraz możliwości dalszego ich rozwoju na poziomie gospodarstw rolnych z uwzględnieniem istniejących barier.

W ramach pracy doktorskiej przeprowadzono badania środowiskowe na terenie Polski, doświadczenie polowe w agroekosystemie kukurydzy z wykorzystanie nawozów mineralnych, naturalnych oraz inhibitorów ureazy i nitryfikacji, jak również badania ankietowe rolników stosujących praktyki prośrodowiskowe.

Wyniki uzyskanych badań środowiskowych wykazały, że praktyki nawozowe wpływające na obieg węgla i azotu w glebach gospodarstw rolnych powinny uwzględniać rankingi ważności zmiennych pod względem ich wpływu na zawartość węgla organicznego i azotu mineralnego. W agroekosystemie kukurydzy największe, istotne statystycznie różnice zaobserwowano w puli azotu w warunkach nawożenia mineralnego oraz stosowania inhibitorów ureazy i nitryfikacji, które zmniejszały emisję N_2O w obiektach z nawozami mineralnymi. Dodatek inhibitorów nie miał natomiast istotnego wpływu mitygacyjnego na uwalniane CO_2 z gleb oraz na zawartość węgla organicznego, kwasów huminowych i humin. Przeprowadzone badania ankietowe potwierdziły, że pomimo występowania barier technicznych, ekonomicznych i informacyjnych, polscy rolnicy mają wystarczającą świadomość prośrodowiskową z zakresu praktyk pozytywnie wpływających na obieg węgla i azotu w rolniczej przestrzeni produkcyjnej.

Polskie warunki glebowo-klimatyczne, jak i powszechnie stosowane praktyki nawozowe niesprzyjające akumulacji węgla organicznego oraz prośrodowiskowemu zarządzaniu azotem w gospodarstwach rolnych wymagają wielowymiarowego podejścia integrującego dalsze badania środowiskowe, wieloletnie doświadczenia polowe z zastosowaniem działań pozytywnie wpływających na obieg C i N oraz analizy postaw interesariuszy w zakresie ich wdrażania.

Słowa kluczowe: węgiel i azot, nawożenie, tlenek diazotu, ditlenek węgla, zrównoważone rolnictwo

Summary

Environmental aspects of the presence of carbon and nitrogen compounds in farms

The use of appropriate practices on farms allows for maintaining optimal concentrations of carbon and nitrogen compounds in soils and limiting their dispersion into the environment. The aims of the research were: a) to identify effective fertilizer practices used in farms that influence the accumulation of organic carbon and mineral nitrogen under Polish environmental conditions, b) to determine the impact of selected fertilizer practices on quantitative and qualitative changes in carbon and nitrogen compounds in the agroecosystem, c) to assess the use of practices limiting the negative impact of plant production on the carbon and nitrogen cycle and the possibilities of extending their use at the farm level, taking into account existing barriers.

As part of the doctoral thesis an environmental study in Poland was carried out. In addition, a field experiment in the maize agroecosystem with mineral and organic fertilizers, urease and nitrification inhibitors was performed, and surveys of farmers using pro-environmental practices were made.

The results of the environmental studies showed that fertilization practices affecting the carbon and nitrogen cycle in farm soils should take into account the importance of rankings of variables in terms of their impact on the concentration of organic carbon and mineral nitrogen. In the maize agroecosystem, the largest, statistically significant differences were observed in the nitrogen pool where mineral fertilization, urease and nitrification inhibitors were used, which reduced N_2O emissions in treatments with mineral fertilizers. However, the addition of inhibitors did not have a significant mitigating effect on CO_2 released from soils or on the content of organic carbon, humins, and humic acids. The conducted surveys confirmed that, despite the existence of technical, economic, and informational barriers, Polish farmers have sufficient pro-environmental awareness of practices that have a positive impact on the carbon and nitrogen cycle in agricultural production space.

Polish soil and climatic conditions as well as commonly used fertilization practices that are unfavorable for the accumulation of organic carbon and pro-environmental nitrogen management on farms require a multidimensional approach integrating further environmental research, long-term field studies using practices that positively impact the C and N cycle and analyzes of stakeholder attitudes towards their implementation.

Key-words: carbon and nitrogen, fertilization, nitrous oxide, carbon dioxide, sustainable agriculture

1. WPROWADZENIE

W ostatnich dekadach świadomość znaczenia kluczowych efektów wywoływanych przez gospodarowanie rolniczą przestrzenią produkcyjną uległa znaczącej transformacji. Przez lata dominującym paradygmatem w produkcji roślinnej była maksymalizacja plonów (Tisdell, 2015). Takie podejście koncentrowało się na jej ilościowych aspektach, pomijając niejednokrotnie kwestie antropogenicznych presji środowiskowych pochodzenia rolniczego. Współczesne badania rolno-środowiskowe w większym stopniu koncentrują się na złożonych interakcjach pomiędzy nawozami, glebą a plonami, nie tylko w kontekście ilości tych ostatnich, ale przede wszystkim potencjalnych konsekwencji dla ekosystemów (Ren i in., 2023).

Z perspektywy produkcyjnej i środowiskowej szczególnego znaczenia nabiera zrównoważona gospodarka węglem organicznym (SOC) i azotem (N), ze względu na ich kluczowy wpływ na zdrowie gleby (Khangura i in., 2023), produktywność upraw (Zhang i in., 2019; Zhou i in., 2022), jakość środowiska (Poláková i in., 2023), a także strategie łagodzenia zmian klimatu i/lub przystosowana się do nich (Ren i in., 2023; Van Hoof, 2023).

Obecne w glebie związki węgla pochodzenia organicznego określane jako glebowa materia organiczna (SOM) kształtują właściwości fizyczne (barwę, gęstość, stabilizację agregatów, retencję wody), fizykochemiczne/chemiczne (wymianę jonową, właściwości buforowe, zasoby, rozpuszczalność i migrację nutrientów, detoksykację środowiska), biologiczne (dostarczanie składników pokarmowych i energii dla mikroorganizmów, biostymulację wzrostu i rozwoju roślin, regulację różnorodności biologicznej) (Ukalska-Jaruga i in., 2017; Lal, 2020). Stanowią one jednocześnie magazyn SOC, akumulujący od 5 do 15% rocznej globalnej emisji ditlenku węgla (CO_2), głównie w substancjach humusowych (HS), które ze względu na rozpuszczalność dzieli się na huminy (nierozpuszczalne ani w kwasach, ani w zasadach), kwasy huminowe (rozpuszczalne w zasadach, a nierozpuszczalne w kwasach) i kwasy fulwowe (rozpuszczalne zarówno w kwasach, jak i w zasadach) (Ukalska-Jaruga i in., 2017; Lal, 2020; Pham i in., 2021). Przyjmuje się, że poziom SOC w strefie korzeniowej, niezbędny do utrzymania funkcji gleb, wynosi 15–20 g kg^{-1} (Lal i in., 2015), podczas gdy ok. 45% gleb mineralnych w Europie charakteryzuje się zawartością SOC poniżej 20 g kg^{-1} (Navarro-Pedreño i in. 2021). W Polsce zgodnie z danymi monitoringowymi średnia zawartość SOC kształtuje się na poziomie 16,7 g kg^{-1} (Monitoring…, 2022).

Nie należy jednocześnie zapominać, że gleby mogą stanowić źródło emisji ditlenku węgla w wyniku respiracji korzeni, oddychania mikroorganizmów heterotroficznych w rizosferze, mineralizacji substancji organicznej indukowanej m.in. wydzielinami korzeniowymi, resztkami roślinnymi i/lub nawożeniem oraz tzw. respiracji podstawowej związanej z metabolizmem oddechowym opartym na mikrobiologicznym rozkładzie SOM. Wymiana gazowa między glebą a atmosferą (tzw. oddychanie gleby) odpowiada za blisko 50% całkowitego odpływu CO_2 z ekosystemów lądowych (Chen i in., 2022; European Commission, 2021). Zrównoważony obieg węgla (C) w środowisku, szczególnie w kontekście gleb uprawnych, jest więc kluczowy w opracowaniu strategii zarządzania, które mogą przyczyniać się do sekwestracji C, równoważąc nadmierną emisje CO_2. Ostatnio podkreśla się, że rolnictwo powinno odgrywać kluczową rolę w osiąganiu unijnego celu usuwania ditlenku węgla w sektorze użytkowania gruntów oraz przyczyniać się do osiągnięcia celu neutralności klimatycznej w Unii Europejskiej (European Commission, 2021).

Przemiany oraz ilość związków organicznych węgla mają wpływ na zawartość azotu w glebach, gdyż ponad 90% N występuje w połączeniach organicznych, z których część (substancje humusowe) pełni także funkcje bufora stabilizującego dostępność tego makroelementu. Organiczne formy azotu podlegają w środowisku glebowym przemianom, a ich końcowymi produktami są mineralne połączenia (N_{min}) dostępne dla roślin – azot amonowy ($N–NH_4$) i azotanowy(V) ($N–NO_3$) (Liang i in., 2023; Valenzuela, 2023). Pomimo że rocznie jedynie 1–3% całkowitej zawartości azotu podlega mineralizacji, to SOM jest ważnym źródłem N_{min}, dostarczając średnio 49-66 kg N ha^{-1} rok^{-1}. Gleby uprawne charakteryzują się przy tym wysoką dynamiką zmian zawartości mineralnych związków azotu determinowaną ich przemianami, tj. pobieraniem przez rośliny, immobilizacją przez mikroorganizmy, nitryfikacją, denitryfikacją, ulatnianiem, wymywaniem i adsorpcją (Dal Molin, i in. 2020). Szczególnie dotyczy to $N-NO_3$, który może być łatwo wymywany, podatny jest również na straty poprzez emisje gazów, a o jego przemianach w wysokim stopniu decydują procesy mikrobiologiczne. Szacuje się, że rolnictwo jest odpowiedzialne za ponad 80% antropogenicznych emisji tlenku diazotu (N_2O) – gazu cieplarnianego charakteryzującego się długim okresem przebywania w atmosferze (ponad 100 lat), który ma 273 razy większy współczynnik globalnego ocieplenia niż CO_2 (Chataut i in. 2023; Ni i in., 2023). Złożoność interakcji między obiegiem SOC i N, powoduje, że nawet niewielkie zmiany w ich dynamice mogą powodować znaczące konsekwencje dla zrównoważonej produkcji roślinnej i jakości środowiska (Zheng i in., 2019). Aplikacja nawozów, uprawa roślin oraz inkorporacja resztek pozbiorowych prowadzą do znaczących, krótkotrwałych zmian w obiegu materii organicznej i przyspieszenia mineralizacji SOM lub immobilizacji C i N. Zawartość oraz stabilność SOC zwiększa się na ogół wraz ze zmniejszaniem frakcji, z którymi jest on związany oraz ze zwiększaniem pH powyżej 5,5 (Solly i in., 2019). W takich warunkach dochodzi również do akumulacji większych ilości azotu. Niestety nadal brakuje informacji lub są one sprzeczne w zakresie wpływu czynników antropogenicznych (nawożenia mineralnego i organicznego roślin uprawianych w plonie głównym i w przedplonie) oraz środowiskowych (odczynu i składu granulometrycznego gleby) na zasoby C i N (Xu i in., 2020). Stąd też szczególnie w kontekście obecnie wprowadzanej inicjatywy rolnictwa węglowego oraz oceny programów działań związanych z dyrektywą azotanową istnieje pilna potrzeba badań dotycząca tych zagadnień w różnych warunkach glebowo-klimatycznych. Należy jednocześnie pamiętać, że nie mogą się one opierać wyłącznie na wiedzy o krajowych czy nawet regionalnych uwarunkowaniach, ale wymagają szczegółowych informacji o ich skutkach oraz wnikliwej oceny możliwości ich wprowadzania na poziomie gospodarstwa rolnego.

Minimalizowane efektów związanych z zaburzeniem cyklu węgla i azotu w agroekosystemach może być dokonywane w gospodarstwach poprzez wprowadzanie praktyk „uszczelniających" go takich jak na przykład aplikacja obornika (FYM) i/lub inhibitorów ureazy i nitryfikacji. Powszechnie uważa się, że stosowanie obornika w dawce 6 – 10 t ha^{-1} rok^{-1} zabezpiecza bezdeficytowy bilans substancji organicznej, a powyżej 13 t ha^{-1} rok^{-1} umożliwia poprawę zasobności gleb w humus (Gonet i Markiewicz, 2007; Bai i in., 2023). Jednocześnie przyczynia się ono do poprawy jakości SOM, tj. do zwiększenia udziału kwasów huminowych i humin i poszerzenia wartości stosunku C_{KH}:C_{KF}. Prowadzi ponadto do pojawienia się dodatkowej puli azotu, którego wykorzystanie przez rośliny w pierwszym roku po zastosowaniu FYM waha się w granicach 20 – 40%. Istnieją również badania wykazujące brak lub niekorzystny wpływ aplikacji FYM, zwłaszcza w połączeniu z nawożeniem mineralnym, na zasoby SOM i straty N (Bai i in., 2023). Dlatego według niektórych autorów (Gross i in., 2021; Bai i in., 2023) zasadne jest prowadzenie dalszych badań, dotyczących zmian ilościowych i jakościowych w zasobach SOC i N pod wpływem stosowania obornika na poziomie gospodarstw rolnych.

Zarówno aplikacja nawozów naturalnych, jak i mineralnych dostarczając do agroekosystemów substratów do reakcji nitryfikacji i denitryfikacji może przyczyniać się do nasilenia gazowych strat N w postaci N_2O. Współczynnik emisji bezpośredniej N_2O z wnoszonego do gleby N – mineralnego i organicznego wynosi 0,01 kg N_2O–N/kg ilości zaaplikowanego azotu (Poland's National Inventory Report, 2023).

Wśród praktyk ograniczających emisje tlenku diazotu pochodzenia nawozowego wymienia się ostatnio aplikację inhibitorów ureazy i/lub nitryfikacji. Ich stosowanie umożliwia spowolnienie lub zatrzymanie enzymatycznego rozkładu mocznika i transformacji N-NH_4 do N-NO_2, co wydłuża okres pozostawania azotu amonowego w formie nieprzekształconej w środowisku glebowym. Pozwala to na zwiększenie efektywności jego wykorzystania przez rośliny i ograniczenie strat N_2O (Akiyama i in., 2009; Gupta i in., 2023). Brakuje przy tym badań kompleksowo oceniających wpływ inhibitorów w warunkach nawożenia organicznego i mineralnego na ilość i jakość związków C i N w glebach oraz emisję CO_2 i N_2O z agroekosystemów.

Należy pamiętać, że oprócz poszukiwania skutecznych praktyk ograniczających negatywny wpływ produkcji roślinnej na obieg węgla i azotu, niezmiernie istotne jest stymulowanie rolników do ich wdrażania na poziomie gospodarstwa. Z badań wykonanych przez Instytut na Rzecz Ekorozwoju wynika, ze niewielki odsetek rolników dostrzega zależność pomiędzy ich działalnością a środowiskiem. Producenci rolni uznają racje prośrodowiskowe werbalnie, natomiast w ograniczonym stopniu kierują się nimi w praktyce. Stąd też kluczową rolę odgrywa wspólna polityka rolna i odzwierciedlające ją krajowe plany strategiczne WPR na lata 2023–2027 zawierające ekoschematy. Praktyki w nich zawarte, realizujące cele środowiskowe i klimatyczne, są dobrowolne dla rolników i dodatkowo płatne w ramach wsparcia bezpośredniego. Ich efektywność w dużym stopniu zależy jednak od utrwalenia wśród rolników prośrodowiskowych postaw i zasad, co z kolei wiąże się ze zidentyfikowaniem barier i motywacji producentów rolnych w zakresie wprowadzania innowacyjnych praktyk rolniczych (Wrzaszcz i Prandecki, 2020; Sharma i in., 2021; Jayaraman i in., 2022; Petsakos i in., 2023).

2. HIPOTEZA I CELE BADAŃ

W niniejszej rozprawie doktorskiej przyjęto następującą hipotezę badawczą:

Zastosowanie odpowiednich praktyk w gospodarstwach rolnych pozwala na utrzymanie optymalnych zawartości związków węgla i azotu w glebach oraz ograniczenie ich rozpraszania w środowisku.

W pracy doktorskiej celami badań były:

1. Identyfikacja skutecznych praktyk nawozowych stosowanych w gospodarstwach rolnych, które wpływają na akumulację węgla organicznego i azotu mineralnego (N_{min}) w polskich warunkach środowiskowych.

2. Określenie oddziaływania wybranych praktyk nawozowych na zmiany ilościowe i jakościowe związków węgla i azotu na przykładzie agroekosystemu kukurydzy.

3. Ocena wdrażania praktyk ograniczających negatywny wpływ produkcji roślinnej na obieg węgla i azotu oraz możliwości dalszego ich rozwoju na poziomie gospodarstw rolnych z uwzględnieniem potencjalnie istniejących barier.

3. MATERIAŁ I METODY BADAŃ

Cele niniejszej pracy doktorskiej zostały zrealizowane w ramach niezależnie przeprowadzonych, lecz powiązanych ze sobą następujących badań:

1. badań środowiskowych (cel 1, praca P.1)
2. doświadczenia polowego (cel 2, praca P.2)
3. badań ankietowych rolników (cel 3, praca P.3).

3.1. Opis badań

Badania środowiskowe

W ramach badań środowiskowych próbki gleby zostały pobrane jesienią (po zbiorach) z 3172 punktów monitoringowych. Rozkład przestrzenny punktów poboru próbek odzwierciedlał zróżnicowane warunki produkcji rolniczej oraz zmienność właściwości polskich gleb. Dwadzieścia próbek pierwotnych składających się na próbkę ogólną pobierano z powierzchni 100 m^2.

Zużycie mineralnych nawozów azotowych oraz obornika w badanych agroekosystemach ustalono podczas wywiadu bezpośredniego z rolnikami.

Doświadczenie polowe

Dwuletnie doświadczenie polowe założono w układzie bloków kompletnie zrandomizowanych w trzech powtórzeniach w gospodarstwie położonym w Piławie Górnej w Polsce na glebach brunatnych (*Cambisols*) o pH 6,5, zawartości SOC 10 g C kg^{-1}, zawartości azotu ogólnego (TN) 1,11 g N kg^{-1} i kationowej pojemności wymiennej 11,28 cm(+) kg^{-1}. Rośliną testową była kukurydza odmiany SY Talisman (FAO 220–230). Schemat doświadczenia, który obejmował 9 obiektów przedstawiono w tabeli nr 1.

Tabela 1. Schemat doświadczenia polowego

Obiekt	Nawożenie mineralne	Nawożenie organiczne	Inhibitor
C	–	–	–
UAN	UAN (150 kg N ha^{-1})	–	–
UAN+UI	UAN (150 kg N ha^{-1})	–	NBPT *
UAN+NI	UAN (150 kg N ha^{-1})	–	DMPP *
UAN+UI+NI	UAN (150 kg N ha^{-1})	–	NBPT+DMPP *
FYM	UAN (150 kg N ha^{-1})	FYM (129 kg N ha^{-1})	–
FYM+UI	UAN (150 kg N ha^{-1})	FYM (129 kg N ha^{-1})	NBPT **
FYM+NI	UAN (150 kg N ha^{-1})	FYM (129 kg N ha^{-1})	DMPP **
FYM+UI+NI	UAN (150 kg N ha^{-1})	FYM (129 kg N ha^{-1})	NBPT+DMPP **

C – kontrola bez nawożenia, UAN –roztwór saletrzano-mocznikowy (RSM), FYM –obornik bydlęcy, UI – inhibitor ureazy, NI – inhibitor nitryfikacji, NBPT – triamid N-(n-butylo)tiofosforowy; DMPP – fosforan 3,4-dimetylopirazolu; *—inhibitor stosowany z nawozem mineralnym; ** – inhibitor stosowany razem z obornikiem bydlęcym

Próbki glebowe (po 25 z każdego poletka) pobierano przed rozpoczęciem doświadczenia i na koniec każdego sezonu wegetacyjnego (po zbiorze roślin).

Badania ankietowe

W badaniach ankietowych zastosowano zintegrowane metody badań percepcji respondentów, które łączyły w sobie strukturalne ankiety oraz pogłębione wywiady indywidualne. Konstrukcja ankiety strukturalnej obejmowała pytania, zarówno demograficzne, jak i faktograficzne sformułowane jako kombinacja pytań zamkniętych i otwartych, a także pytań wymagających oceny za pomocą skali Likerta. Zakres pytań dotyczył wieku rolnika (pytanie typu zamkniętego), poziomu wykształcenia rolnika (pytanie typu zamkniętego), powierzchni gospodarstwa (pytanie typu zamkniętego), typu gospodarstwa (pytanie typu zamkniętego), specjalizacji produkcji gospodarstwa (pytanie otwarte), postawy rolnika wobec: zastosowania zróżnicowanej struktury upraw, metod bezorkowych, roślin okrywowych i międzyplonów, inkorporacji obornika do gleby w ciągu 12 godzin od aplikacji, stosowania nawozów naturalnych płynnych metodami alternatywnymi do rozbryzgowej oraz przyorywania słomy (pytania oceniane za pomocą skali Likerta); oceny subiektywnej przez rolnika istotności: poprawy poziomu zasobów SOC w glebie; zwiększenia poziomu zasobów N w glebie; ograniczenia zanieczyszczenia wód gruntowych oraz atmosfery; postrzegania biurokracji i kontroli; wpływu dopłat finansowych na zastosowanie środków przyjaznych dla środowiska i klimatu (pytania oceniane na rankingowej skali 10-punktowej).

Podczas indywidualnych wywiadów pogłębionych, respondenci byli dodatkowo proszeni o odpowiedź na sześć pytań z zakresu analizowanych praktyk prośrodowiskowych i proklimatycznych, w kontekście ograniczenia rozpraszania C i N z rolnej przestrzeni produkcyjnej, a mianowicie czy zamierzają stosować lub już stosują: zróżnicowaną strukturę upraw, metody uprawy bezorkowej, rośliny okrywowe i międzyplony, inkorporację obornika do gleby w ciągu 12 godzin od aplikacji, aplikację gnojowicy z użyciem technik innych niż rozbryzgowe, przyorywanie słomy.

W zależności od odpowiedzi afirmatywnych lub negatywnych, uczestnicy byli proszeni o udzielanie wyjaśnień dotyczących ich decyzji odnośnie możliwości stosowania badanych praktyk.

3.2. Metody badań laboratoryjnych

W pobranych i odpowiednio przygotowanych próbkach glebowych oznaczono następujące właściwości: pH w 1 mol KCl dm^{-3} metodą potencjometryczną w stosunku gleba:roztwór 1:2,5, węgiel organiczny – metodą Tiurina w modyfikacji Simakowa, azot ogólny – metodą Kjeldahla, zawartość azotu azotanowego(V) i azotu amonowego metodą spektrofotometryczną z zastosowaniem autoanalizatora Skalar San Plus System, skład frakcyjny substancji humusowych metodą Schnitzera, skład granulometryczny metodą dyfrakcji laserowej.

Emisje CO_2 i N_2O z gleby mierzono *in situ* (30 pomiarów rocznie) przy użyciu statycznej komory respiracyjnej podłączonej do spektrometru gazowego GASMET GT5000 Terra (Gasmet Technologies Oy, Vantaa, Finlandia). Strumienie emitowanych gazów mierzono na losowo wybranych punktach każdego poletka doświadczalnego między godziną 11:00 a 13:00, aby wyeliminować zmienność dobową. W celu wyznaczenia dobowej emisji z powierzchni jednego hektara, zastosowano ekstrapolacje linową pomiędzy wykonanymi pomiarami.

3.3. Analiza statystyczna wyników badań

W badaniach środowiskowych oraz w doświadczeniu polowym wykorzystano jednoczynnikową analizę wariancji (ANOVA) oraz test istotności Tukeya z poziomem istotności $\alpha = 0,05$ przy użyciu programu Statistica 13.3. Na rysunkach literami a, b i c oznaczono grupy jednorodne średnich; średnie z tą samą literą nie różnią się istotnie przy $\alpha = 0,05$.

W analizie wyników badań środowiskowych w celu wyodrębnienia rankingów ważności zmiennych pod względem ich wpływu na zawartość węgla organicznego i azotu mineralnego zastosowano metodę CART w programie Statistica 13.3..

W badaniach ankietowych przeprowadzono analizę głównych składowych (PCA) przy użyciu środowiska R z pakietem FactomineR w programie RStudio.

4. OMÓWIENIE WYNIKÓW I DYSKUSJA

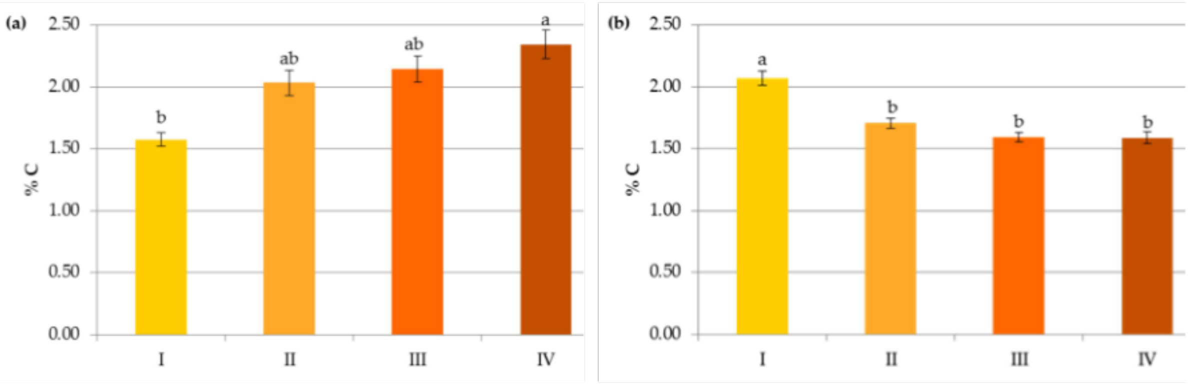
4.1. (Praca P.1.) Glebowe związki węgla i azotu w polskich warunkach rolno-środowiskowych

Wiązania węgla w formie glebowych związków organicznych oraz akumulacja azotu w agroekosystemach są uwarunkowane zmiennym w czasie ukształtowaniem się czynników antropogenicznych związanych przede wszystkim z nawożeniem roślin uprawnych oraz środowiskiem przyrodniczym.

4.1.1. Praktyki nawozowe wpływające na zawartość związków węgla i azotu w glebach gospodarstw rolnych

Nawożenie organiczne i mineralne należy do czynników w największym stopniu decydujących o zawartości związków węgla i azotu w agroekosystemach.

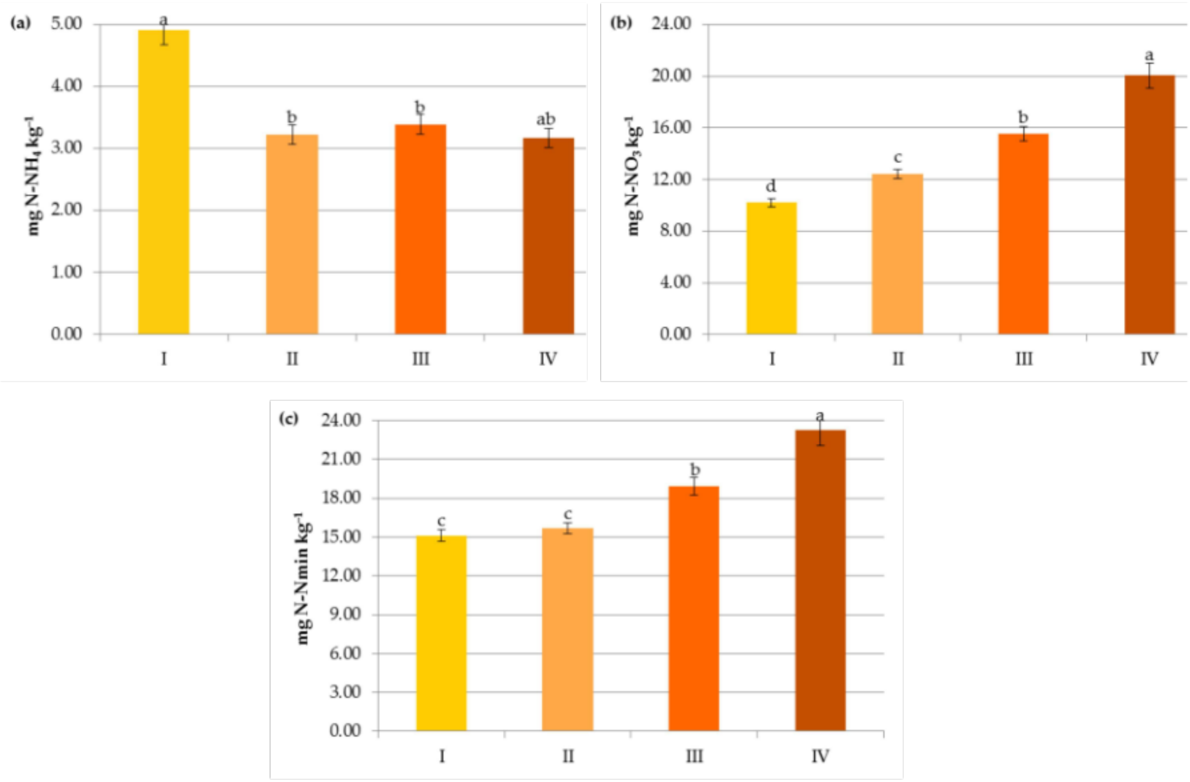
W przeprowadzonych badaniach środowiskowych istotnie najwięcej węgla organicznego (2,34%) kumulowały gleby w warunkach aplikacji obornika w dawce powyżej 150 kg N ha^{-1} (rys. 1a). Należy podkreślić, że obecnie w Polsce zużycie obornika utrzymuje się na poziomie ok. 40 kg na 1 ha użytków rolnych. Pozytywne oddziaływanie obornika na zawartość SOC jest spowodowane wprowadzaniem z nim materii organicznej o korzystnych składzie (zawartości kwasów humusowych, lignin i polifenoli oraz o optymalnych wartościach stosunku C:N), jak również jego pośrednim oddziaływaniem na zwiększone plonowanie roślin uprawnych i wielkość pozostawianych resztek pozbiorowych (Majumder i in., 2018; Mustafa i in., 2021).



Rysunek 1. Zawartość SOC w warunkach stosowania obornika (a) oraz nawozów azotowych mineralnych (b). I: <50 kg N ha^{-1}, II: 50–100 kg N ha $^{-1}$, III: 100–150 kg N ha^{-1}, IV: >150 kg N ha^{-1}

Odmienne wyniki w zakresie oddziaływania wzrastających dawek N na zawartość SOC, odnotowywano przy aplikacji mineralnych nawozów azotowych pod plon główny i przedplon. Po przekroczeniu 50 kg N ha^{-1}, tj. w średnim zakresie stosowanym w Polsce (GUS, 2024), obserwowano istotne obniżenie zawartości węgla organicznego w glebie – o 14,7–23,2% (rys. 1b). Mogło być to spowodowane nasileniem mineralizacji SOM w wyniku zawężenia wartości stosunku C:N (Ladha i in., 2011; Plaza-Bonilla i in., 2013), zakwaszeniem gleby (Kuzyakov i in., 2021), a także negatywnymi zmianami w stabilności agregatów i/lub w aktywności mikroorganizmów glebowych (Ren i in., 2014). Niektórzy badacze wskazują, że aplikacja nawozów azotowych nasila akumulację C w ekosystemach rolniczych tylko wtedy, gdy jest ona uzupełniona o praktyki z zakresu rolnictwa węglowego, takie jak przyorywanie słomy (Plaza-Bonilla i in., 2013; Wang i in., 2018).

W odróżnieniu od korzystnego oddziaływania obornika na gromadzenie węgla organicznego w agroekosystemach, nie stwierdzono jego istotnego wpływu na zawartość mineralnych form azotu. Ich zasoby w badanych glebach gospodarstw rolnych były natomiast istotnie różnicowane stosowanym nawożeniem mineralnym (rys. 2).



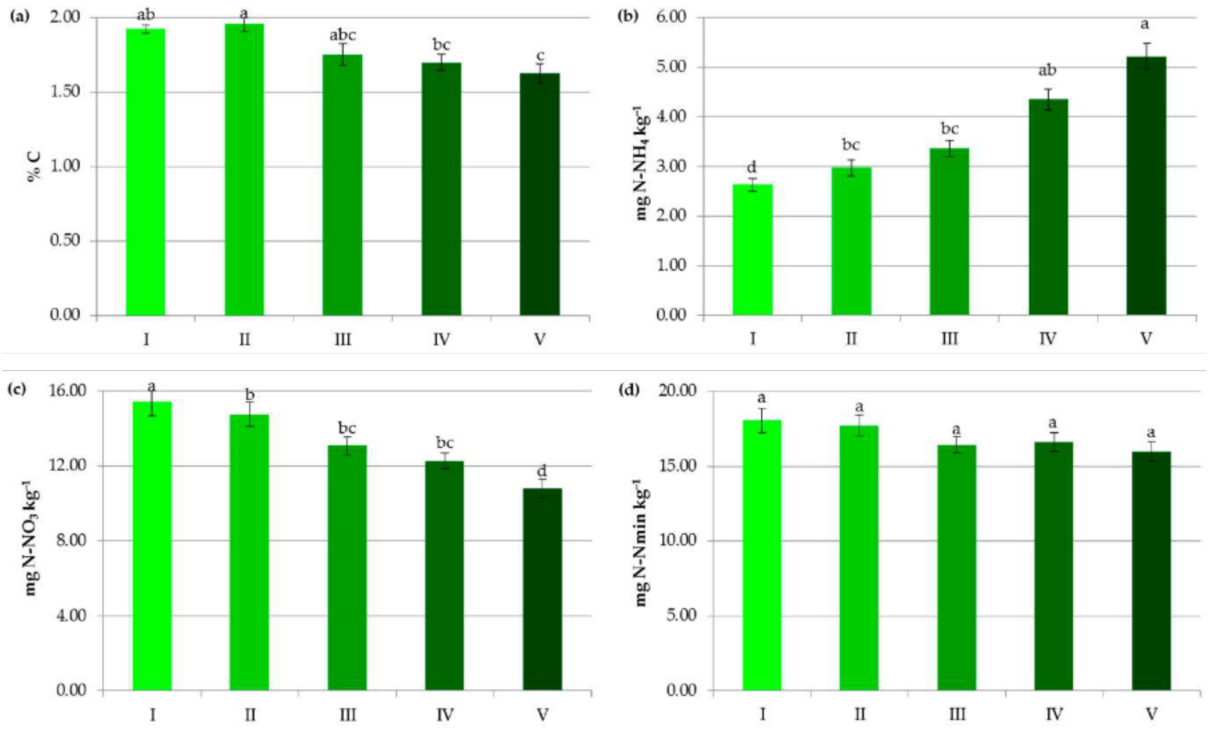
Rysunek 2. Wpływ stosowania nawozów azotowych mineralnych na zawartość N-NH$_4$ (a), N-NO$_3$ (c), oraz N$_{min}$ (d) w glebach. I: <50 kg N ha^{-1}, II: 50–100 kg N ha $^{-1}$, III: 100–150 kg N ha^{-1}, IV: >150 kg N ha^{-1}.

Najwięcej N_{min} i N-NO_3 występowało w glebach nawożonych N mineralnym w ilości powyżej 150 kg N ha^{-1} zarówno w przypadku roślin uprawianych w plonie głównym jak i przedplonie (rys. 2b i 2c). Warto zaznaczyć, że statystycznie istotne zwiększenie zawartości N-NO_3 miało miejsce już po przekroczeniu dawki nawozowej 50 kg N ha^{-1} (rys. 2b). Pula N-NH_4 zmniejszyła się jednak wówczas o ponad 30% i pozostawała na stałym poziomie wraz ze wzrostem dawek N (rys. 2a). Było to niewątpliwie spowodowane zmianami w dynamice przemian azotu, tj. mineralizacją, nitryfikacją, denitryfikację i ulatnianiem pod wpływem nawożenia mineralnego (Lu i in. 2021).

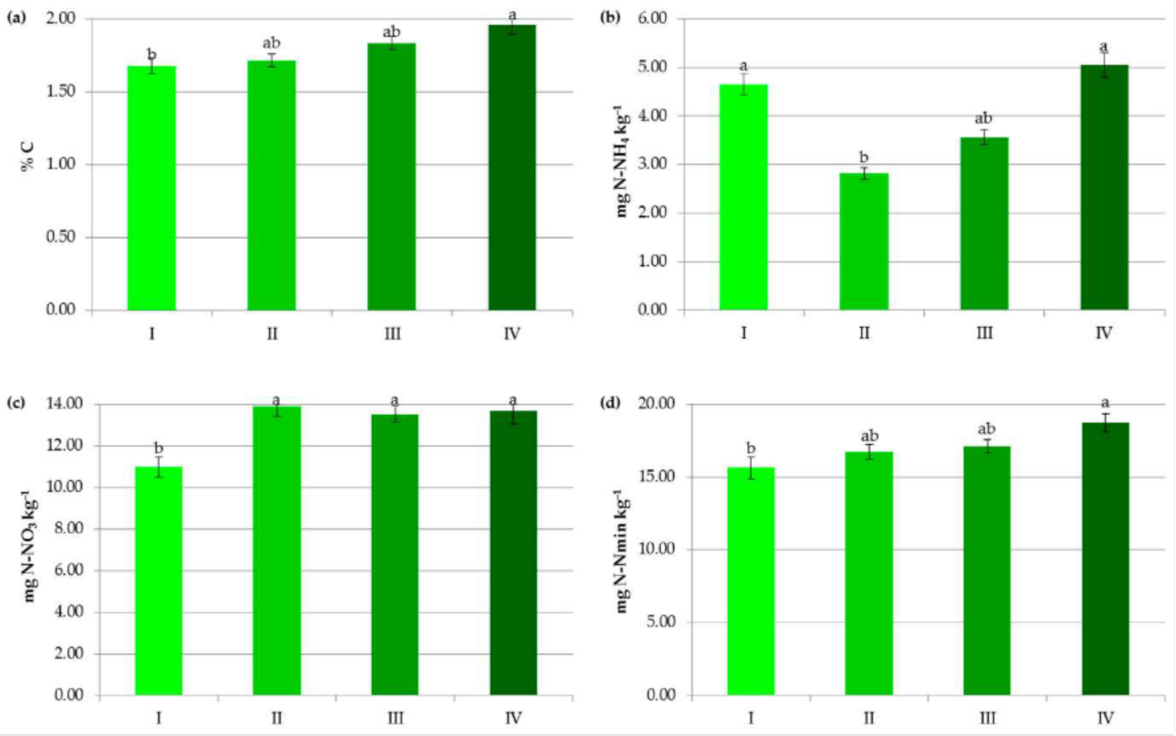
4.1.2. Czynniki środowiska przyrodniczego wpływające na zawartość związków węgla i azotu w agroekosystemach

W przeprowadzonych badaniach środowiskowych zasoby węgla i azotu były istotnie modyfikowane przez warunki glebowe panujące w Polsce. Średnia zawartość SOC wynosiła 1,78% i ulegała statystycznie istotnemu obniżeniu przy odczynie kwaśnym i bardzo kwaśnym (rys. 3a) oraz w glebach bardzo lekkich (rys. 4a). Wyższe wartości pH przyczyniają się do optymalizacji środowiska wzrostu roślin, zwiększenia wykorzystania makro- i mikroelementów z zasobów glebowych oraz nawozów, a tym samym stymulują produkcję biomasy (Filipek i in., 2015; Paradelo i in., 2015). Uzyskane w badaniach współczynniki korelacji pomiędzy plonami roślin a pH i SOC ($r = 0{,}886$ i $r = 0{,}759$) wydają się potwierdzać te mechanizmy. Według niektórych autorów (Paradelo i in., 2015) większy dopływ resztek pożniwnych do gleb wapnowanych kompensuje początkowe straty SOM, spowodowane zwiększoną jej mineralizacją. Ponadto w glebach o wyższych wartościach pH substancje humusowe są przekształcane w bardziej stabilne kompleksy organiczno-mineralne, co poprawia efektywność fizycznej ochrony materii organicznej (Filipek i in., 2015; Kuzyakov i in., 2021) i zmniejsza ryzyko związane z emisją CO_2.

Zgodnie z opiniami niektórych autorów gleby bogate we frakcje iłową i pyłową charakteryzują się również wolniejszą mineralizacją SOM (Wiesmeier i in., 2019; Kögel-Knabner i Amelung, 2021). Otrzymane w niniejszych badaniach wyniki są zgodne z rezultatami doświadczeń prowadzonych w innych częściach Europy. Matus (2021) opierając się na analizie 1,5 miliona próbek gleb pobranych z francuskich pól uprawnych stwierdził, że 85% zawartości SOC zostało związanych w nich we frakcji drobnoziarnistej <20 μm.



Rysunek 3. Wpływ pH gleby na zawartość SOC (a), N-NH₄ (b), N-NO₃ (c), oraz N_{min} (d). I: pH > 7,2, II: pH=6,6–7,2, III: pH=5,6–6,5, IV: pH=4,6–5,5, V: pH < 4,5.

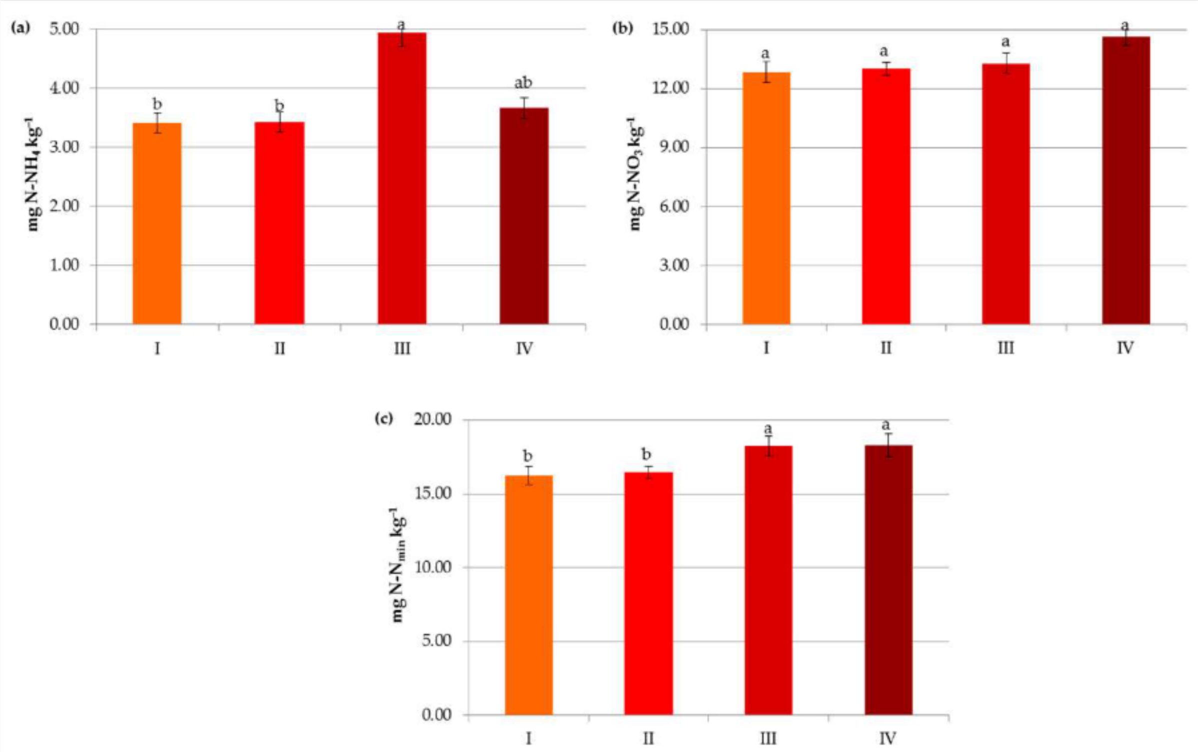


Rysunek 4. Wpływ uziarnienia gleby na zawartość SOC (a), N-NH₄ (b), N-NO₃ (c), oraz N_{min} (d). % frakcji < 0,02 mm — I : < 10%, II: 10–20%, III : 20–35%, IV: > 35%.

W przeprowadzonych badaniach wykazano, że zawartość N_{min} była kształtowana przez te same czynniki środowiska przyrodniczego, które regulują poziom SOM. Obniżeniu pH gleb towarzyszyło zmniejszenie zawartości azotanów (z 15,43 mg kg^{-1} przy pH > 7,2 do 10,79 mg kg^{-1} przy pH < 4,5) i wzrost zawartości $N\text{-}NH_4$ (z 2,63 mg kg^{-1} przy pH > 7,2 do 5,22 mg kg^{-1} przy pH < 4,5) (rys. 3b i c). Wskazywać to może na ograniczenie tempa nitryfikacji w glebach zakwaszonych. W niektórych eksperymentach, przy pH<5,5 kationy NH_4^+ powstałe w wyniku mineralizacji SOM akumulowały się w profilu gleby (Aciego Pietri i Brookes, 2008), a warunki zasadowe sprzyjały nitryfikacji i podwyższeniu stężenia azotanów(V) w roztworze glebowym (Wang i in., 2019). Należy zauważyć, że wyższe wartości pH gleb znacząco wpływają na pobieranie $N\text{-}NO_3$ przez rośliny, ale mogą także intensyfikować procesy ich wymywania i/lub gazowych strat N (Wang i in., 2019; Zhu i in., 2019), co powinno być uwzględniane przy podejmowaniu decyzji dotyczących zarządzania tym składnikiem na poziomie gospodarstw rolnych.

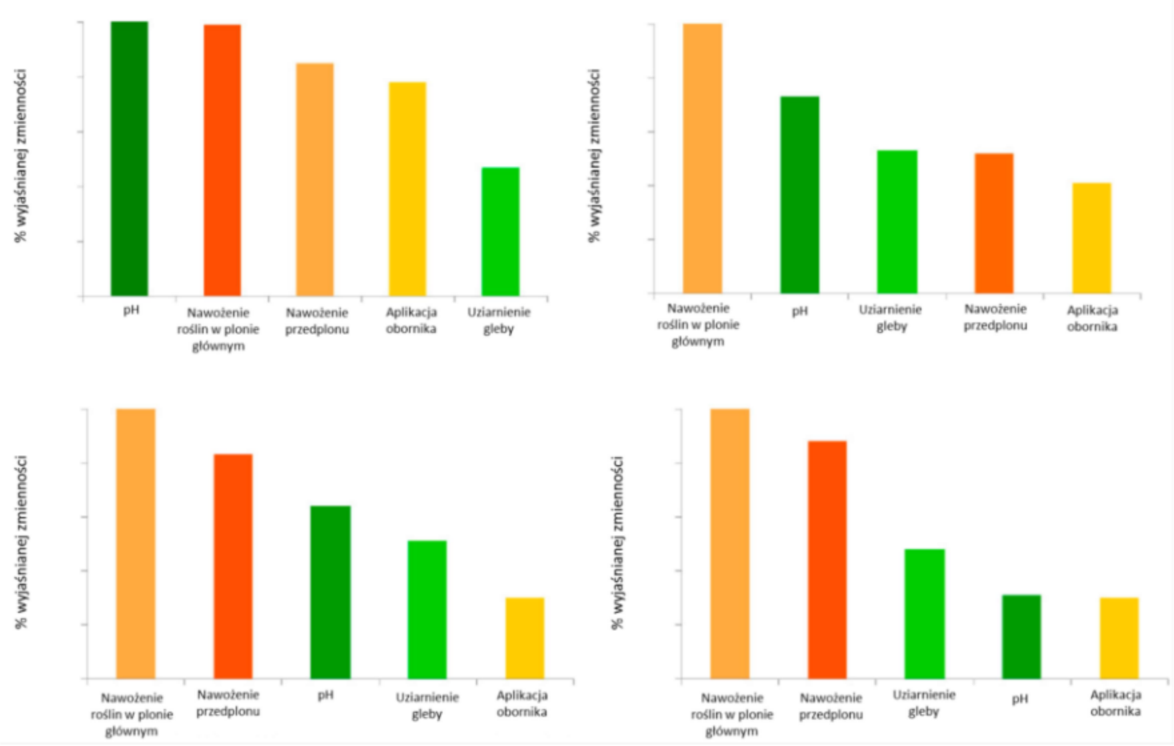
Przeprowadzone badania środowiskowe wykazały, że uziarnienie gleby było również czynnikiem istotnie kształtującym pulę $N\text{-}NH_4$ i $N\text{-}NO_3$ w glebach (Rysunek 4b–d). Zawartość azotu amonowego ulegała zwiększeniu zarówno w glebach ciężkich, jak i lekkich, wskazując na zróżnicowanie procesów ją kontrolujących (rys. 4b). Gleby bogate we frakcję o średnicy poniżej 0,02 mm mają większą zdolność sorpcji wymiennej i niewymiennej $N\text{-}NH_4$ (Cai i in., 2021). Gleby ubogie w nią z kolei charakteryzują się wyższym tempem mineralizacji SOM i są przeważnie kwaśne, co ogranicza biologiczne utlenianie $N\text{-}NH_4$. Odmiennie kształtowały się natomiast zawartości $N\text{-}NO_3$, których najniższy poziom (średnio 10,98 mg kg^{-1}) był notowany w glebach bardzo lekkich (rys. 4c), gdzie obserwuje się nasilone przemieszczanie azotanów w głąb profilu glebowego wraz z infiltrującą wodą i zakwaszenie niesprzyjające nitryfikacji.

W przeprowadzonych badaniach środowiskowych glebowa materia organiczna istotnie wpływała na zawartość mineralnych form azotu (rys. 5a–c), Według Ladha i in. (2011) mineralizacja SOM może zapewnić, w zależności od praktyk agronomicznych, nawet połowę zapotrzebowania roślin na N. Największe ilości N_{min} były gromadzone w glebach zawierających powyżej 2% C (rys. 5c). Wykazano przy tym, że zawartość $N\text{-}NH_4$ była niższa i bardziej zróżnicowana w poszczególnych klasach węgla w porównaniu z $N\text{-}NO_3$ (rys. 5a i b). Wynika to z odmiennego charakteru przemian obu tych form N w agroekosystemach. Azot amonowy jest sorbowany w postaci wymiennej i niewymiennej, ulega nitryfikacji oraz jest preferowany przez mikroorganizmy w procesie immobilizacji, dzięki czemu w mniejszym stopniu ulega rozpraszaniu w środowisku (Soussana i Lemaire, 2014; Zhu i in., 2019).



Rysunek 5. Wpływ poziomu SOC na zawartość N-NH$_4$ (a), N-NO$_3$ (c), oraz N$_{min}$ (d) w glebach. I: <1% SOC, II:1–2% C, III:3–6% C, IV—>6% C.

Zastosowanie metody CART w analizie wyników badań środowiskowych pozwoliło wyodrębnić następujący rankingów ważności zmiennych pod względem ich wpływu na zawartość węgla organicznego w glebach: pH gleby > przedplonowe nawożenie mineralne > nawożenie mineralne roślin w plonie głównym > aplikacja obornika > uziarnienie gleby (rys. 6a). Znaczenie tych predyktorów w odniesieniu do zasobów azotu mineralnego było nieco odmienne, tj. zarówno w przypadku N-NH$_4$, jak i N-NO$_3$ najważniejszą zmienną było nawożenie mineralne (rys. 6b i c).



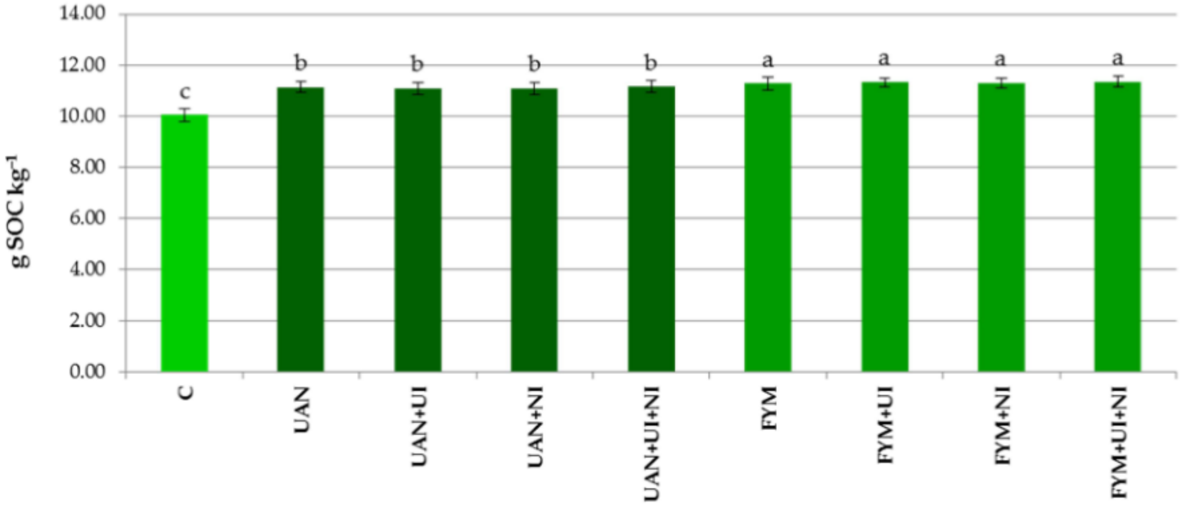
Rysunek 6. Rankingów ważności zmiennych pod względem ich znaczenia dla zawartości SOC (a), $N\text{-}NH_4$ (b), $N\text{-}NO_3$ (c) i N_{min} (d).

4.2. (Praca P.2.) Wpływ wybranych praktyk nawozowych na zmiany ilościowe i jakościowe związków węgla i azotu na przykładzie agroekosystemu kukurydzy

Analizowane w badaniach środowiskowych praktyki nawozowe, tj. stosowanie nawozów naturalnych (obornika) oraz mineralnych dodatkowo wzbogacone o czynnik ograniczający rozpraszanie azotu w środowisku, tj. inhibitory ureazy i nitryfikacji, zostały wykorzystane w doświadczeniu polowym. Eksperyment ten założono na glebie ciężkiej o pH=6,5, która zgodnie z uzyskanymi wcześniej rezultatami charakteryzuje się optymalnymi warunkami środowiskowymi z punktu widzenia potencjału zarządzania zasobami węgla i azotu. Gatunkiem testowym była kukurydza – jedna z najważniejszych i najczęściej uprawianych roślin w Polsce o wysokich wymaganiach pokarmowych, przyczyniającą się do degradacji SOM.

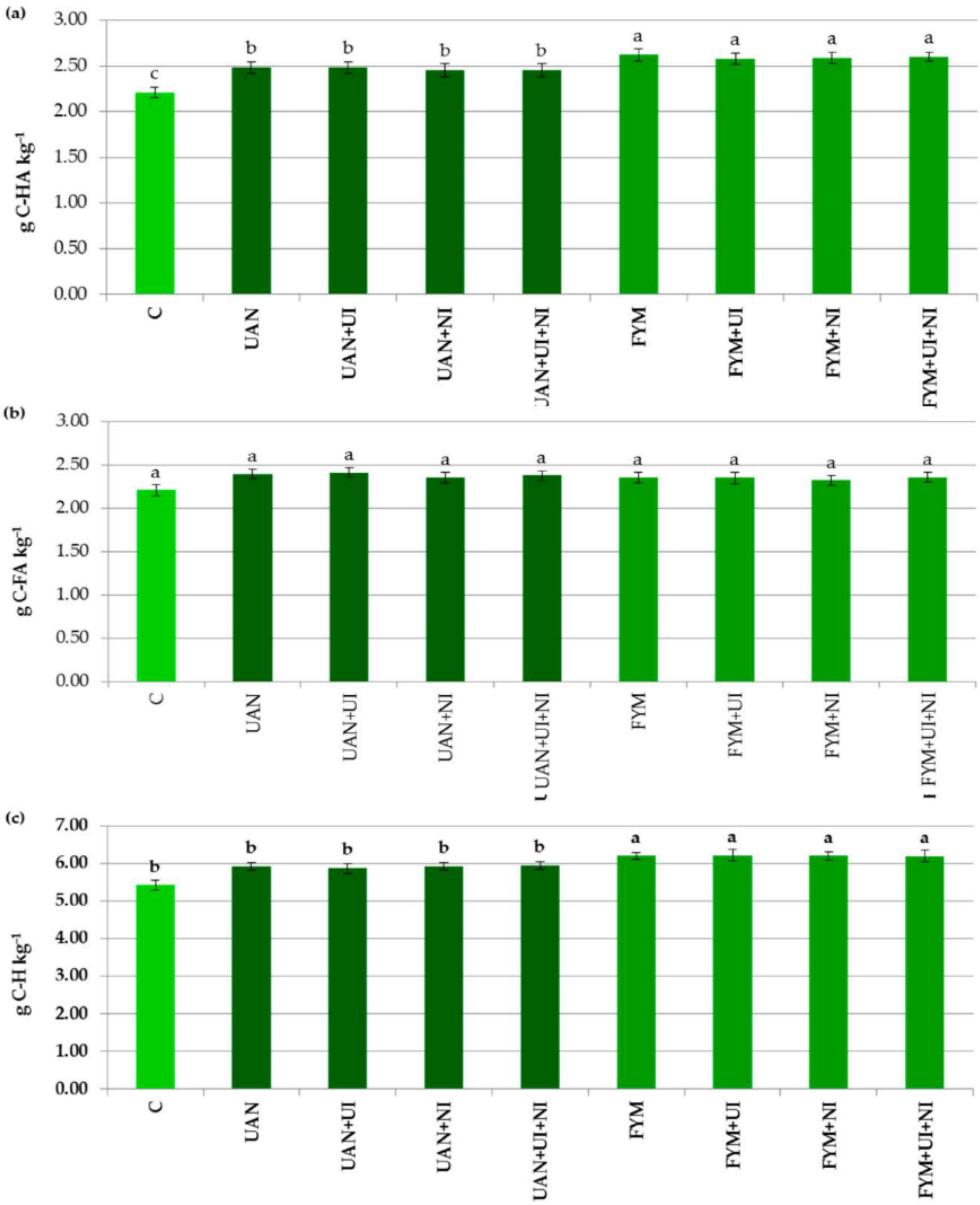
4.2.1. Zawartość związków węgla w glebie agroekosystemu kukurydzy

W przeprowadzonym doświadczeniu polowym stwierdzano istotnie wyższą zawartość SOC (11,28 g kg^{-1}) w glebie nawożonej obornikiem w połączeniu z nawozami mineralnymi, w odniesieniu do wartościami uzyskanymi w obiekcie kontrolnym (nienawożonym) (rys. 7). Było to niewątpliwie związane z dodatkową ilości C i N wprowadzoną z nawozami i/lub zwiększeniem plonów oraz wyższym dopływem tych składników wraz z ryzodepozycją i resztkami pozbiorowymi (Šimanský i in., 2019; Abdalla i in., 2022). Należy przy tym zaznaczyć, że aplikacja inhibitorów ureazy i nitryfikacji nie miały istotnego wpływu na poziom SOC w środowisku glebowym (rys. 7).



Rysunek 7. Zawartość SOC w warunkach nawożenia. C–obiekt kontrolny (bez nawożenia), UAN – roztwór saletrzano-mocznikowy; UI – inhibitor ureazy; NI – inhibitor nitryfikacji; FYM – obornik

Odnotowano także zmiany jakościowe związków węgla. Istotne różnice w oddziaływaniu nawożenia organicznego i mineralnego stwierdzono jedynie w przypadku zawartości kwasów huminowych (C-HA) i humin (C-H) (rys. 8a i c). UI i NI nie wykazywały przy tym istotnego oddziaływania na frakcje substancji humusowych. Stosunki C-HA i C-FA wyrażone w postaci wskaźnika humifikacji (HI) wskazywały, że intensywność humifikacji była większa w glebach nawożonych FYM (1,10-1,12) w odniesieniu do poletek z RSM (1,0-1,04). Według niektórych autorów (Ukalska-Jaruga i in. 2017), wartości HI >1 są charakterystyczne dla gleb, w których dominują procesy humifikacji; wyższe wartości tego wskaźnika świadczą o ich większej żyzności.

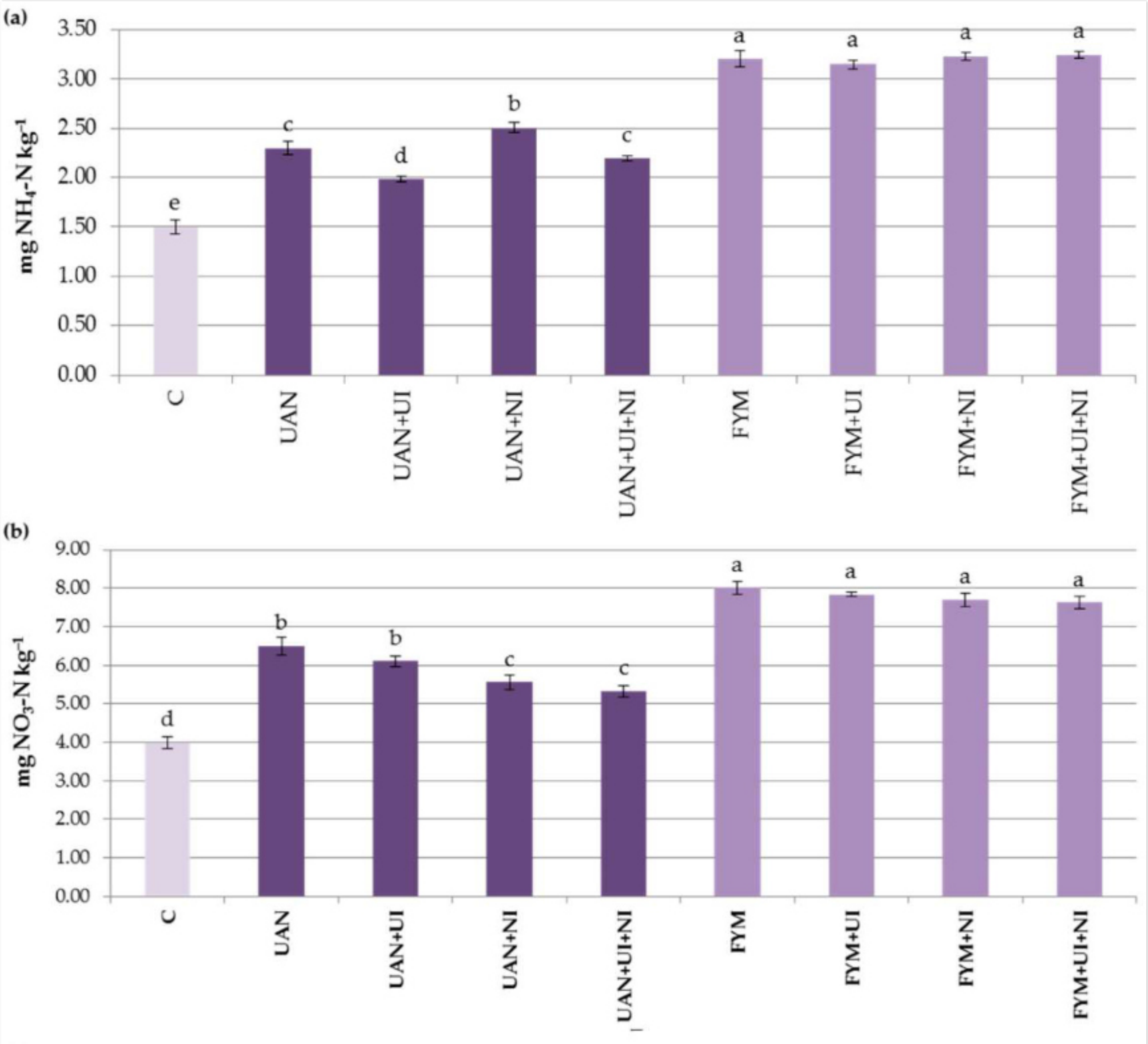


Rysunek 8. Zawartość C-HA (a), C-FA (b) oraz C-H (c) w glebie. C–obiekt kontrolny (bez nawożenia), UAN – roztwór saletrzano-mocznikowy; UI – inhibitor ureazy; NI – inhibitor nitryfikacji; FYM – obornik

4.2.2. Zawartość związków azotu w glebie agroekosystemu kukurydzy

Podobnie jak w przypadku zasobów SOM, zastosowanie obornika istotnie różnicowało zawartość azotu ogólnego oraz mineralnych form N. Poziom SOC wykazywał pozytywną korelację z TN ($r=0,930$, $p<0,001$), N-NH$_4$ ($r=0,790$, $p<0,001$) i N-NO$_3$ ($r=0,818$, $p<0,001$).

W przeprowadzonym doświadczeniu polowym największe zawartości N-NO$_3$ i N-NH$_4$ odnotowano w glebach obiektów nawożonych FYM, odpowiednio 7,70-8,01 mg kg^{-1} i 3,15-3,24 mg kg^{-1} (rys. 9). Dodatek inhibitorów wpływał na obniżenie wartości tych parametrów, nie zostało to jednak udowodnione statystycznie.



Rysunek 9. Zawartość N-NH$_4$ (a) oraz N-NO$_3$ (b) w glebie. C–obiekt kontrolny (bez nawożenia), UAN – roztwór saletrzano-mocznikowy; UI – inhibitor ureazy; NI – inhibitor nitryfikacji; FYM – obornik

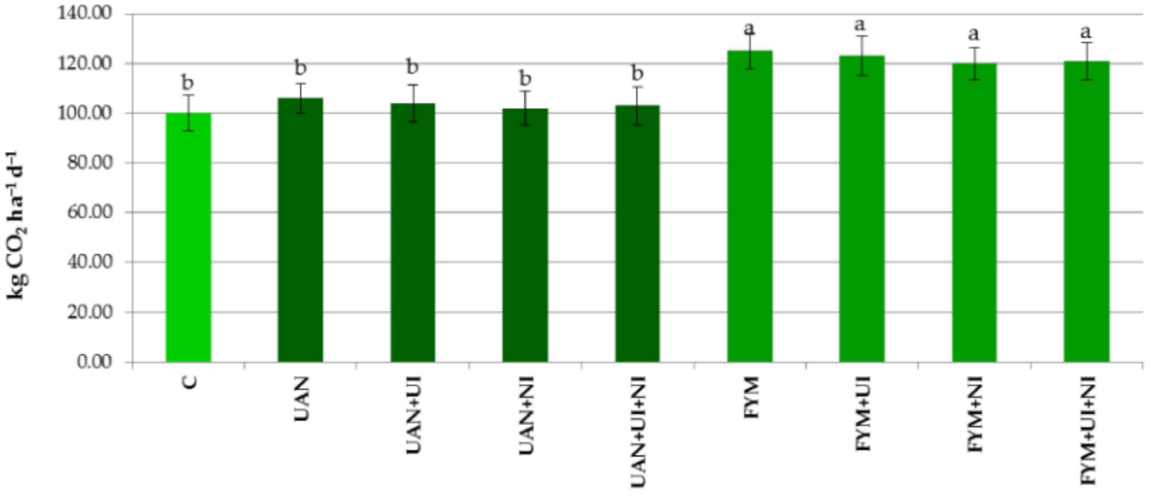
Zastosowanie NBPT z roztworem saletrzano mocznikowym przyczyniło się do obniżenia zawartości obu analizowanych mineralnych form azotu (rys. 9), dzięki spowolnieniu hydrolizy mocznika (Gupta i in., 2023). Stopniowe pojawianie się jonów NH_4^+, umożliwiło niewątpliwie ich efektywniejsze wykorzystanie przez rośliny, ograniczając jednocześnie stopień nitryfikacji i potencjalne straty NO_3^- (Guardia i in., 2018; Gupta i in., 2023).

Dodanie DMPP do nawozu RSM ograniczało nitryfikację w glebie, zwiększając zawartość $N\text{-}NH_4$ o 8,70% i obniżając poziom $N\text{-}NO_3$ o 14,46% (ryc. 9). DMPP wydłuża czas przebywania jonów amonowych w glebie poprzez dezaktywację enzymu odpowiedzialnego za pierwszy etap nitryfikacji, czyli utlenianie $N\text{-}NH_4$ do NH_2OH (Guardia i in., 2018; Cui i in., 2022; Hao i in., 2023; Li i in., 2023; Ma i in., 2023).

4.2.3. Emisje ditlenku węgla i tlenku diazotu w agroekosystemie kukurydzy

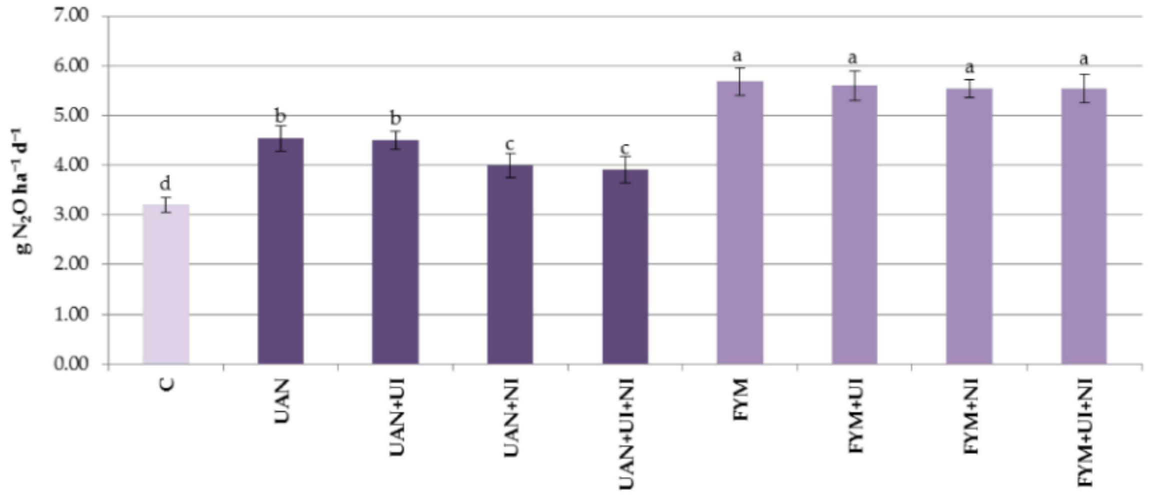
W przeprowadzonym doświadczeniu polowym zaobserwowano zmiany nie tylko w puli węgla i azotu glebowego, ale także w emisji ich gazowych związków, tj. CO_2 i N_2O. Emisja ditlenku węgla wahała się w granicach 100-125 kg CO_2 ha^{-1} d^{-1} (rys. 10). Nienawożone obiekty wykazały najniższe straty węgla w postaci CO_2. Nie stwierdzono jednocześnie istotnych zmian w tym względzie pomiędzy poletkami kontrolnymi a wartościami uzyskanymi na obiektach z nawozami mineralnymi – UAN, UAN+UI, UAN+NI i UAN+UI+NI (rys. 10). Dodatek DMPP i NBPT do roztworu saletrzano-mocznikowego również nie miał istotnego wpływu na ten parametr. Brak wpływu inhibitorów nitryfikacji i ureazy na ilość wydzielanego z gleb CO_2 obserwowali w swoich badaniach także inni autorzy Huérfano i in. (2015) oraz Wang i in. (2020).

Zastosowanie obornika istotnie zwiększało emisję CO_2 z gleby w porównaniu do obiektów UAN i C (rys. 10); niewątpliwie głównie na skutek zwiększonego tempa mineralizacji dostarczonej wraz z tym nawozem materii organicznej. Należy przy tym podkreślić, że pomimo tego, poziom SOC w glebie obiektów z FYM był istotnie wyższy w odniesieniu do wartości uzyskanych na poletkach nawożonych N mineralnym. Odnotowano przy tym istotne korelacje pomiędzy emisją CO_2 a zawartościami SOC ($r=0,622$), TN ($r=-0,794$), C-HA ($r=0,833$), C-H ($r=0,844$), $N\text{-}NH_4$ ($r=0,921$) i $N\text{-}NO_3$ ($r=0,932$). W badaniach innych autorów (Abbasi i in., 2022) również dowiedziono, że dostępność i jakość związków C i N są kluczowymi czynnikami mineralizacji substancji organicznej w glebach.



Rysunek 10. Emisja CO_2 w agroekosystemie kukurydzy. C–obiekt kontrolny (bez nawożenia), UAN – roztwór saletrzano-mocznikowy; UI – inhibitor ureazy; NI – inhibitor nitryfikacji; FYM – obornik

W przeprowadzonym doświadczeniu polowym najwyższą emisję tlenku diazotu odnotowano na obiekcie nawożonym obornikiem (5,68 g ha^{-1} day^{-1}), a najniższą na poletkach kontrolnych 3,20 g ha^{-1} day^{-1} (Rysunek 11b). Było to najwidoczniej uwarunkowane większą ilości azotu dostarczonego do agroekosystemu w tym pierwszym przypadku. Nie należy również zapominać, że obornik stanowi źródło stosunkowo łatwo dostępnego węgla zwiększającego aktywność bakterii nitryfikacyjnych i denitryfikacyjnych (Dong i in., 2022).



Rysunek 11. Emisja N_2O w agroekosystemie kukurydzy. C–obiekt kontrolny (bez nawożenia), UAN – roztwór saletrzano-mocznikowy; UI – inhibitor ureazy; NI – inhibitor nitryfikacji; FYM – obornik

Zastosowanie inhibitorów ureazy i nitryfikacji wraz z obornikiem nie wpłynęło istotnie na emisję N_2O, która kształtowała się w przedziale 5,54-5,59 g ha^{-1} dzień$^{-1}$ (rys. 11). Badania innych autorów również nie wykazały takiego wpływu (Halvorson i in. 2011) ze względu na stopniowe uwalnianie mineralnych form azotu z FYM oraz absorpcję lub nasilony rozkład inhibitorów w obecności podwyższonej zawartości związków organicznych.

Emisja N_2O z obiektów nawożonych RSM kształtowała się na poziomie 4,54 g ha^{-1} dzień$^{-1}$, a aplikacja inhibitorów DMPP i NBPT+DMPP istotnie ją ograniczyła, odpowiednio o 11,89% i 13,88% (ryc. 11). Według Cui i in. (2022) oraz Ma i in. (2023) DMPP, charakteryzujący się niską mobilnością, powolną biodegradacją i trwałością w środowisku glebowym, stosowany z nawozami na bazie mocznika znacząco hamuje potencjał nitryfikacji.

Dodatek NBPT do RSM obniżył wartości emisji N_2O z agroekosystemu kukurydzy, chociaż redukcja ta nie został udowodniona statystycznie (rys. 11). Mogło to wynikać z dużej zawartości frakcji iłowe i pyłowej w badanej glebie. Według niektórych autorów (Gupta i in. 2023; Ma i in. 2023) inhibitory NBPT i DMPP są bardziej efektywne w ograniczaniu emisji N_2O na glebach lekkich aniżeli ciężkich, ze względu na większe wiązanie inhibitorów w tym drugim przypadku.

W przeprowadzonym doświadczeniu polowym stwierdzono dodatnie korelacje pomiędzy emisją N_2O a zawartościami SOC (r= 0,786), TN (r=0,884), C-HA (r= 0,931), C-H (r=0,907), N-NH_4 (r= 0,924) i N-NO_3 (r= 0,987), co było zgodne z wynikami innych badań (Halvorson i in.; 2011; Abbasi i in., 2022).

Należy pamiętać, że praktyki nawozowe w różny sposób wpływają na emisje gazów cieplarnianych i zależności pomiędzy emisjami CO_2 i N_2O a właściwościami gleby nie są uniwersalne (Abbasi i in., 2022).

4.3. (Praca P.3.) Wdrażania praktyk ograniczających negatywny wpływ produkcji roślinnej na obieg węgla i azotu na poziomie gospodarstw rolnych

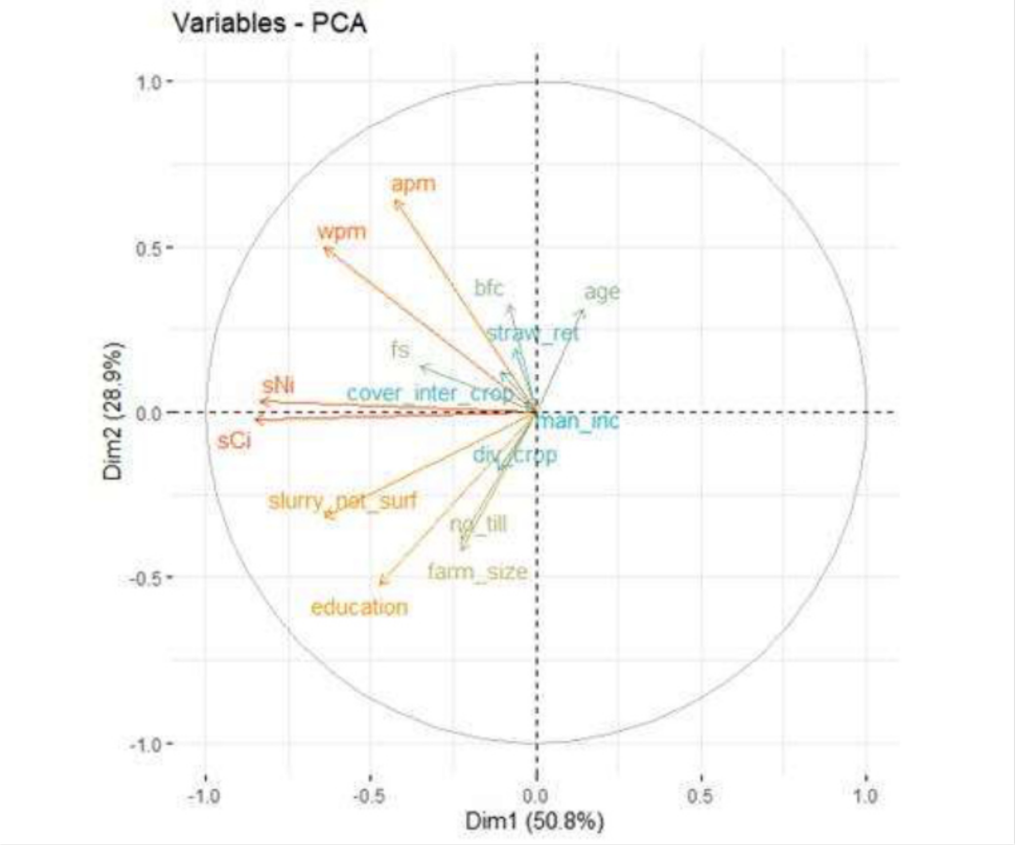
W przeprowadzonych badaniach ankietowych uwzględniono praktyki prośrodowiskowe i proklimatyczne realizowane w ramach najczęściej stosowanego przez polskich rolników Ekoschematu *Rolnictwo węglowe i zarządzanie składnikami odżywczymi* (79,6% spośród wszystkich wskazanych ekoschematów w Agencji Restrukturyzacji i Modernizacji Rolnictwa) (Styburski i in. 2023; Ustawa…2023). Pozwoliło to na identyfikację czynników wpływających na ich implementację w naszym kraju.

Badania ankietowe wykazały znaczne zróżnicowanie w percepcji praktyk rolniczych w gospodarstwach. Spośród sześciu uwzględnionych działań, pięć otrzymało pozytywne oceny od ponad 60% respondentów, co świadczy o dużym potencjale ich wdrażania (tab. 2). Dotyczyło to przede wszystkim zróżnicowanej struktury upraw, uprawy międzyplonów i wsiewek śródpolnych oraz doglebowej inkorporacji słomy (tab. 2). Rolnicy wyrażali chęć implementacji tych praktyk przede wszystkim ze względu na zwiększenie zasobów węgla i azotu (w przypadku dwóch pierwszych) w glebie (tab. 2, rys. 12).

Warto zauważyć, że ponad 50% respondentów negatywnie oceniła uprawę bezorkową, co sugeruje, że jej wdrażanie może napotykać większe trudności w porównaniu z pozostałymi działaniami realizowanymi w ramach ekoschematu. Głównym powodem negatywnych opinii na jej temat było wyraźne przywiązanie rolników do tradycyjnych metod uprawy (tab. 2). Druga najczęściej wymieniana przez nich bariera to brak odpowiednich maszyn (21,31% ankietowanych), a następnie niedostrzeganie korzyści ekonomicznych i środowiskowych z jej wdrożenia (12,3% respondentów). Warto zwrócić uwagę, że postawa ta utrzymywała się pomimo świadomości respondentów odnośnie potencjalnych korzyści związanych ze zwiększaniem zawartości SOM w warunkach uprawy bezpłużnej (rys. 12). Odmienne wyniki badań uzyskano w Tennessee, USA, (Lo i in., 2021), gdzie uprawa bezorkowa była preferowana przez rolników w stosunku do stosowania międzyplonów i wsiewek śródpolnych. Warto przy tym zwrócić uwagę na istnienie dodatniej korelacji między poziomem wykształcenia rolników a ich pozytywnym nastawieniem do wprowadzania uprawy bezpłużnej w analizowanych gospodarstwach. Kluczowe w zmianie nastawienia producentów rolnych do tej praktyki może się więc okazać podejmowanie działań na rzecz podnoszenia ich świadomości.

Tabela 2. Odpowiedzi uzyskane w wyniku pogłębionych wywiadów przeprowadzonych wśród ankietowanych rolników (n = 122)

Praktyka rolno-środowiskowa	Odpowiedzi IDI po kategoryzacji	Udział respondentów [%]	n
Zróżnicowana struktura upraw	Tak, aby zwiększyć bioróżnorodność	17,21	21
	Tak, aby zwiększyć zapasy SOC w dłuższej perspektywie	50,82	62
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	22,95	28
	Nie, z powodu jednolitego profilu produkcyjnego	3,28	4
	Nie, z powodu wielkości uprawianego obszaru i trudności technicznych	4,10	5
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	1,64	2
Uprawa bezorkowa	Tak, aby zredukować rozkład SOM	14,75	18
	Tak, aby zwiększyć aktywność mikrobiologiczną gleby	19,67	24
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	7,38	9
	Nie, z powodu braku odpowiednich maszyn	21,31	26
	Nie, z powodu przywiązania do tradycyjnej formy uprawy gleby	24,59	30
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	12,30	15
Międzyplony i wsiewki śródpolne	Tak, aby zmniejszyć ryzyko wymywania N-NO$_3$ do wód gruntowych	11,48	14
	Tak, aby zwiększyć glebową zasobność w SOC	47,54	58
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	15,57	19
	Nie, z powodu wzrostu kosztów uprawy	18,03	22
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	7,38	9
Wymieszanie obornika z glebą w ciągu 12 godzin od aplikacji	Tak, aby zmniejszyć emisję amoniaku i gazów cieplarnianych	14,75	18
	Tak, aby zmaksymalizować sorpcję N-NH$_4$ w glebie	38,52	47
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	9,02	11
	Nie, z powodu zbyt dużego obszaru i trudności technicznych	18,85	23
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	11,48	14
	Nie, z powodu niemożności wyprodukowania / nabycia obornika	7,38	9
Aplikacja nawozów naturalnych płynnych metodą inną niż rozbryzgowa	Tak, aby zmniejszyć emisję amoniaku i gazów cieplarnianych	21,31	26
	Tak, aby zmaksymalizować sorpcję N-NH$_4$ w glebie	36,07	44
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	12,30	15
	Nie, z powodu zbyt dużego obszaru i trudności technicznych	3,28	4
	Nie, z powodu braku odpowiednich maszyn	13,11	16
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	6,56	8
	Nie, z powodu niemożności wyprodukowania / nabycia takich nawozów	7,38	9
Wymieszanie słomy z glebą	Tak, aby zwiększyć glebową zasobność w SOC	39,34	48
	Tak, aby zwiększyć aktywność mikrobiologiczną gleby	23,77	29
	Tak, przede wszystkim aby otrzymać dodatkowe dotacje	6,56	8
	Nie, z powodu potrzeby używania słomy w chowie ściółkowym	18,85	23
	Nie, z powodu używania resztek pożniwnych do celów produkcji energii	4,92	6
	Nie, z braku widocznych korzyści ekonomicznych i środowiskowych	6,56	8



Rysunek 12. Wykres ładunków czynnikowych analizy składowych głównych.
Długość każdego wektora wskazuje jakość zmiennych na mapie czynników. Kąt między wektorami wskazuje na korelację między danymi zmiennymi: blisko 0 stopni dla silnej korelacji dodatniej, blisko 180 stopni dla silnej korelacji ujemnej i blisko 90 stopni dla słabej lub bliskiej zeru korelacji. Skróty: sCi – wzrost glebowej zasobności w C; sNi – wzrost glebowej zasobności w N; wpm – łagodzenie zanieczyszczenia wody; apm – łagodzenie zanieczyszczenia powietrza; bfc – biurokracja, formalności, kontrole; fs – dotacje finansowe; div_crop – zróżnicowana struktura upraw; no_till – uprawa bezorkowa; cover_inter_crop - uprawy okrywowe i międzyplony; man_inc – wprowadzanie obornika do gleby w ciągu 12 godzin po aplikacji; slurry_not_surf – aplikacja gnojowicy bez rozprowadzania na powierzchni; straw_ret – inkorporacja słomy

Według ankietowanych głównym argumentem przekonywującym ich do wdrażania praktyk związanych ze stosowaniem nawozów naturalnych, tj. wymieszania obornika z glebą w ciągu 12 godzin od aplikacji oraz aplikacji nawozów naturalnych płynnych metodą inną niż rozbryzgowa, jest zwiększenie sorpcji N-NH_4 w glebach. Należy przy tym zaznaczyć, że znaczenie zwiększenia zasobów N jako czynnika wpływającego na skłonność rolników do stosowania praktyk z tym związanych dominowała głównie w przypadku gospodarstw z produkcją roślinną.

Część respondentów (14,75%-21,31%) wskazywała również na środowiskowe korzyści związane ze zmniejszeniem gazowych strat N w związku z wdrożeniem tych dwóch działań uwzględniających aplikację nawozów naturalnych, szeroko opisywaną przez wielu badaczy (Velthof & Mosquera, 2011; Hou i in., 2015).

Przeprowadzone badania ankietowe potwierdziły, że polscy rolnicy mają wystarczającą świadomość środowiskową z zakresu praktyk pozytywnie wpływających na obieg węgla i azotu w rolniczej przestrzeni produkcyjnej. Napotykają niekiedy jednak na bariery techniczne, ekonomiczne i informacyjne, których przezwyciężenie pozwoli na stosowanie tych praktyk w większym zakresie (Sikora, 2021; Cuadros-Casanova i in., 2023)

5. WNIOSKI I STWIERDZENIA

1. W polskich warunkach rolno-środowiskowych istotnie najwięcej węgla organicznego gromadziły gleby nawożone obornikiem w dawce powyżej 150 kg N ha^{-1}, tj. poniżej średniego zużycia tego nawozu w naszym kraju. Istotne zmniejszenie wartości tego wskaźnika występowało natomiast już po przekroczeniu 50 kg N ha^{-1} zastosowanych w postaci nawozów mineralnych.

2. Istotnie największe ilości azotu mineralnego akumulowały gleby nawożone azotem mineralnym w dawkach powyżej 150 kg N ha^{-1} stosowanych pod rośliny uprawiane w plonie głównym i przedplonie. Nawożenie obornikiem nie wywierało istotnego wpływu na zwartość azotu amonowego i azotanowego(V) w środowisku glebowym.

3. Praktyki nawozowe wpływające na obieg węgla i azotu w glebach gospodarstw rolnych powinny uwzględniać rankingi ważności zmiennych pod względem ich wpływu na:
   - zawartość SOC: pH gleby > przedplonowe nawożenie mineralne > nawożenie mineralne roślin w plonie głównym > aplikacja obornika > uziarnienie gleby,
   - poziom azotu mineralnego: nawożenie mineralne roślin w plonie głównym > przedplonowe nawożenie mineralne > uziarnienie gleby > pH gleby>aplikacja obornika.

4. Pomimo że gleby nawożone obornikiem w większym stopniu emitowały związki węgla i azotu do atmosfery w postaci CO_2 i N_2O aniżeli obiekty z nawozem mineralnym RSM, zawierały jednocześnie wyższe zawartości węgla organicznego, kwasów huminowych, humin, azotu ogólnego, amonowego i azotanowego(V).

5. W agroekosystemie kukurydzy największe, istotne statystycznie różnice zaobserwowano w puli azotu w warunkach nawożenia mineralnego oraz stosowania inhibitorów ureazy i nitryfikacji, które zmniejszały emisję

N_2O w obiektach z RSM. Dodatek inhibitorów nie miał natomiast istotnego wpływu mitygacyjnego na CO_2 oraz na zawartość węgla organicznego, kwasów humusowych i huminowych, co może świadczyć o występowaniu ich adsorpcji, szybszej degradacji i obniżeniu efektywności w obecności podwyższonej zawartości związków organicznych.

6. Przeprowadzone badania ankietowe potwierdziły, że pomimo występowania barier technicznych, ekonomicznych i informacyjnych, polscy rolnicy mają wystarczającą świadomość prośrodowiskową z zakresu praktyk pozytywnie wpływających na obieg węgla i azotu w rolniczej przestrzeni produkcyjnej. Zwiększenie zasobów tych dwóch składników w glebach stanowi kluczowy czynnik determinujący gotowość producentów rolnych do ich wdrażania.

7. Polskie warunki glebowo-klimatyczne jak i powszechnie stosowane praktyki nawozowe niesprzyjające akumulacji węgla organicznego oraz prośrodowiskowemu zarządzaniu azotem w gospodarstwach rolnych wymagają wielowymiarowego podejścia integrującego dalsze:
    - badania środowiskowe,
    - wieloletnie doświadczenia polowe z zastosowaniem praktyk pozytywnie wpływających na obieg C i N,
    - analizy postaw interesariuszy w zakresie ich wdrażania.

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7. PUBLIKACJE WCHODZĄCE W SKŁAD ROZPRAWY DOKTORSKIEJ Z OŚWIADCZENIAMI DOKTORANTA ORAZ WSPÓŁAUTORÓW DOTYCZĄCYCH ICH WKŁADU W PRZYGOTOWANIE OPUBLIKOWANYCH PRAC NAUKOWYCH

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Soil Organic Carbon and Mineral Nitrogen Contents in Soils as Affected by Their pH, Texture and Fertilization

Sebastian Kuśmierz [1], Monika Skowrońska [1,*], Przemysław Tkaczyk [1,*], Wojciech Lipiński [2] and Jacek Mielniczuk [3]

[1] Department of Agricultural and Environmental Chemistry, University of Life Sciences in Lublin, Akademicka 15, 20-950 Lublin, Poland
[2] National Chemical–Agricultural Station in Warsaw, Żółkiewskiego 17, 05-075 Warszawa, Poland
[3] Department of Applied Mathematics and Computer Science, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland
* Correspondence: monika.skowronska@up.lublin.pl (M.S.); przemyslaw.tkaczyk@up.lublin.pl (P.T.)

Abstract: Soil organic carbon (SOC) and mineral nitrogen (N_{min}), especially nitrates (NO_3^-) in agroecosystems have attracted much attention over the past few decades due to their crucial roles in soil fertility, crop productivity, environmental quality, and/or climate change mitigation and adaptation. The aim of the study was to evaluate the contents of organic carbon, ammonium, and nitrate in soils under differentiated pH, texture, and fertilization rates. A large-scale environmental study was conducted in Polish arable lands. The spatial distribution of the sampling points reflected agricultural production conditions, variability of soil properties, and representativeness of textures that are characteristic of Poland. Our results indicated that SOC content was significantly affected by the soil pH and texture as well as mineral and organic fertilization. The same factors, except organic amendments, significantly supported mineral nitrogen concentration in the present study. The most important factors controlling SOC in the study were ranked as follows: soil pH > pre-crop N fertilization > crop N fertilization > N applied with manure > soil texture. In the case of $N\text{-}NH_4$ and $N\text{-}NO_3$, mineral fertilization was the most critical variable. The carbon and nitrogen governance in agroecosystems should consider the ranks of factors controlling their contents.

Keywords: soil organic matter; ammonium; nitrate; manure; nitrogen fertilizer

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1. Introduction

Soil organic carbon (SOC) and mineral nitrogen (N_{min}), especially nitrates (NO_3^-) in agroecosystems, have attracted much attention over the past few decades due to their crucial roles in soil fertility, crop productivity, environmental quality, and/or climate change mitigation and adaptation [1–6].

The soil carbon (C) pool, estimated at 2293 Pg, including 1425 Pg of SOC to 1 m depth, is the third principal C stock, which accumulates 5–15% of the annual global C emissions [2,7,8]. In merely the topsoil of EU farmland, 51 billion tons of CO_{2eq} are stored, which is equivalent to over ten times the European Union's annual emissions. SOC content is crucial to diverse soil functions (physical, chemical, and biological) and ecosystem services [1–3,9–11], e.g., (i) soil structure and aggregation, (ii) water use efficiency and retention, (iii) plant nutrient availability, (iv) the diversity and biological activity of soil organisms, and (v) gaseous emissions/sequestration. The critical level of SOC in the root zone, essential to maintaining these functions, is 1.5–2.0% [12], whereas ca. 45% of the mineral soils in Europe have low or very low SOC content, i.e., below 2% [13].

Nitrogen (N) is both an essential element strongly related to food security and resource sustainability that often limits crop yields and a major pollutant in modern agroecosystems [5,14–16]. It is the most unstable plant nutrient, especially its mineral forms, subjected to many transformations sometimes in a short time, such as uptake by plants, immobilization by microorganisms, nitrification, denitrification, volatilization, leaching, and adsorption [17]. Approximately 25% of the N inputs are emitted into the air, and nearly 20% are leached as nitrate, hampering productivity and profitability of crop production as well as environmental quality [15]. Anthropogenic activities have doubled the global rates of reactive N applications in the last century and substantially affected C and N cycles in agricultural ecosystems [7]. Unfortunately, there are lack or contradictory reports regarding the effect of anthropogenic (fertilization with manure, crop, and pre-crop fertilization with mineral nitrogen) and environmental (soil pH and texture) factors on C and N pools [6,18]. Mineral fertilizers, affecting the increase in crop yields and the amount of post-harvest residues, have a positive effect on the SOC content. Some authors [19,20], however, believe that one-sided mineral fertilization, especially in light soils, causes intensification of mineralization. Exogenous organic matter is another possible significant source of SOC and N_{min} in agroecosystems. On the other hand, the direction of such impact is determined by its chemical composition, mainly the content of N, polyphenols, and lignins [19]. Adjusting the pH by liming allows the retention of C and N in the soil. It is also a factor that potentially generates gaseous losses in the form of carbon dioxide, nitrogen oxides, dinitrogen oxide, ammonia, and/or dissolved forms of C and N [21–23]. Hence, there is a need to investigate these issues in various climatic and soil conditions and to update research allowing the implementation of effective mitigation and adaptation measures in the context of the currently introduced carbon farming initiative as a part of the European Green Deal and the evaluation of action programs related to the Nitrates Directive (91/676/EEC).

The aim of the study was to (i) evaluate the contents of organic carbon, ammonium, and nitrate in soils under differentiated pH, texture, and fertilization rates and (ii) identify the variables that were most important in contributing to the accumulation of carbon and mineral nitrogen in Polish soils using a novel analytical approach in large-scale research.

2. Materials and Methods

Soil samples were taken in the autumn after harvesting crops at 3172 permanent monitoring points evenly covering Polish arable lands (Figure 1), from 0–30 cm depth and an area of 100 m^2. The spatial distribution of the sampling points reflected agricultural production conditions, variability of soil properties, and representativeness of textures that are characteristic of Poland. The consumption of mineral nitrogen fertilizers (urea and ammonium nitrate), as well as farmyard manure (FYM) in the studied agroecosystems established following the procedure of soil monitoring in Poland (a direct interview with farmers) varied from <50 kg N ha^{-1} to >150 kg N ha^{-1}.

Poland belongs to the same climate zone as the Czech Republic, Slovakia, partly Germany and Austria, Hungary, Romania, Ukraine, and Belarus [24]. The annual rainfall during the investigation was 573.3 mm. Mean monthly temperatures in January and June were: -1.5 and 21.2 °C, respectively.

Each sample taken from the fields for analysis consisted of 20 primary soil samples collected from the surface layer from an area of 100 m^2. Soil samples were air-dried, homogenized, sieved (2 mm sieve-mesh), and kept in the dark. The soil samples for N_{min} analysis were placed in polyethylene bags and stored in the refrigerator.

In air-dried and sieved soil samples, the following parameters were determined: pH in 1 mol KCl dm^{-3} by the potentiometric method in a soil:solution ratio of 1:2.5 (*w*/*v*), total organic carbon by sulfochromic oxidation with titration of excess $K_2Cr_2O_7$ with $FeSO_4(NH_4)_2SO_4 \cdot 6H_2O$, and particle size distribution using the laser diffraction method (LDM) based on the light intensity distribution pattern of the scattered light emitted from that particle group. Mineral nitrogen was determined colorimetrically (N-NO_3 with diphenylamine sulfonic acid and N-NH_4 with Nessler's reagent) using a San Plus Segmented Flow Analyzer after extraction with 1% of K_2SO_4 [25,26].

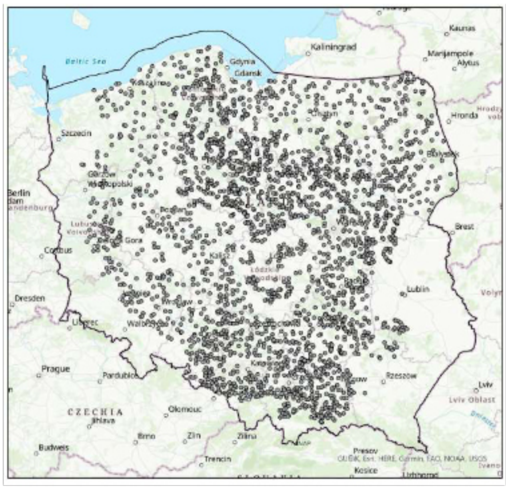

Figure 1. Map of the study and sampling area.

In order to compare the average value of parameters in individual classes, one-way analysis of variance (ANOVA) and Tukey's honest significant difference test with significance level $\alpha = 0.05$ were performed. The importance of variables was assessed by CART, which is a multivariate regression tool appropriate for identifying the most important factors controlling SOC and N_{min} contents in soils. Statistical analyses were performed using Statistica 13.3.

3. Results and Discussion

Carbon and mineral nitrogen accumulation in soils depended on soil pH, texture as well as mineral and organic fertilization (Figures 2–8).

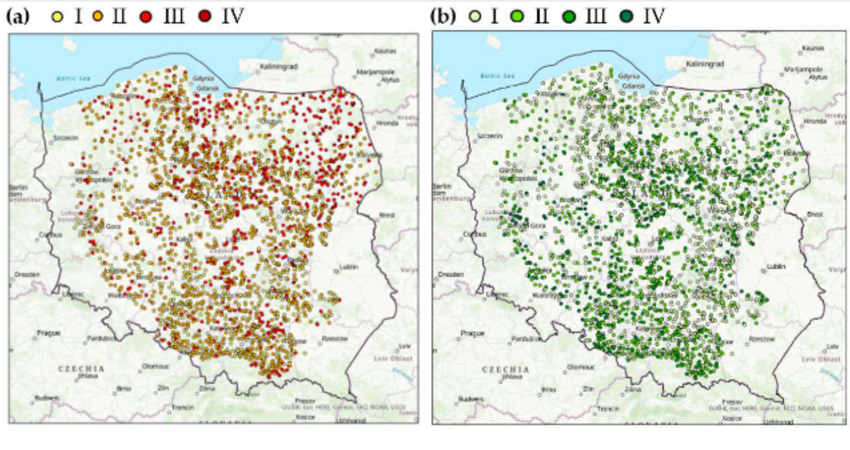

Figure 2. *Cont.*

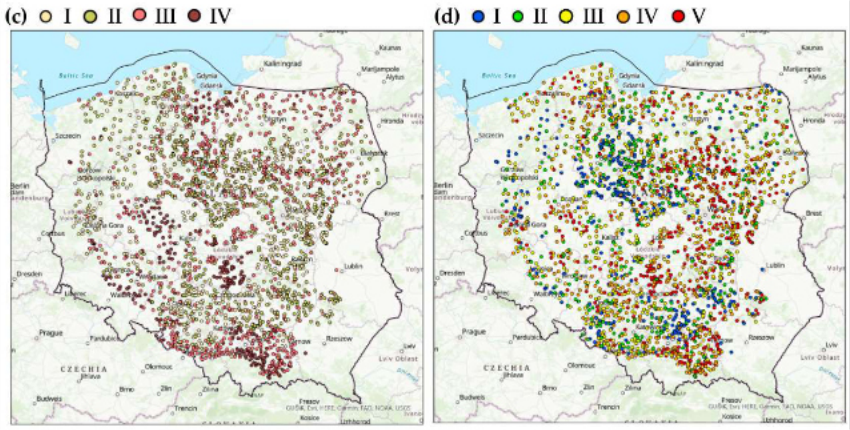

Figure 2. The soil characteristic distribution among the sites (**a**) organic carbon: I—<1% C (very low), II—1–2% C (low), III—3–6% C (medium), IV—>6% C (high), (**b**) mineral nitrogen: I—<10 mg kg^{-1}, II—10.01–20.0 mg kg^{-1} III—20.01–40.0 mg kg^{-1}, I—>40.0 mg kg^{-1}, (**c**) fractions smaller than 0.02 mm: I—<10%, II—10–20%, III—20–35%, IV—>35%, (**d**) soil pH: I—alkaline soils, pH > 7.2, II—neutral soils, pH = 6.6–7.2, III—slightly acidic soils, pH = 5.6–6.5, IV—acidic soils, pH = 4.6–5.5, V–highly acidic soils, pH < 4.5.

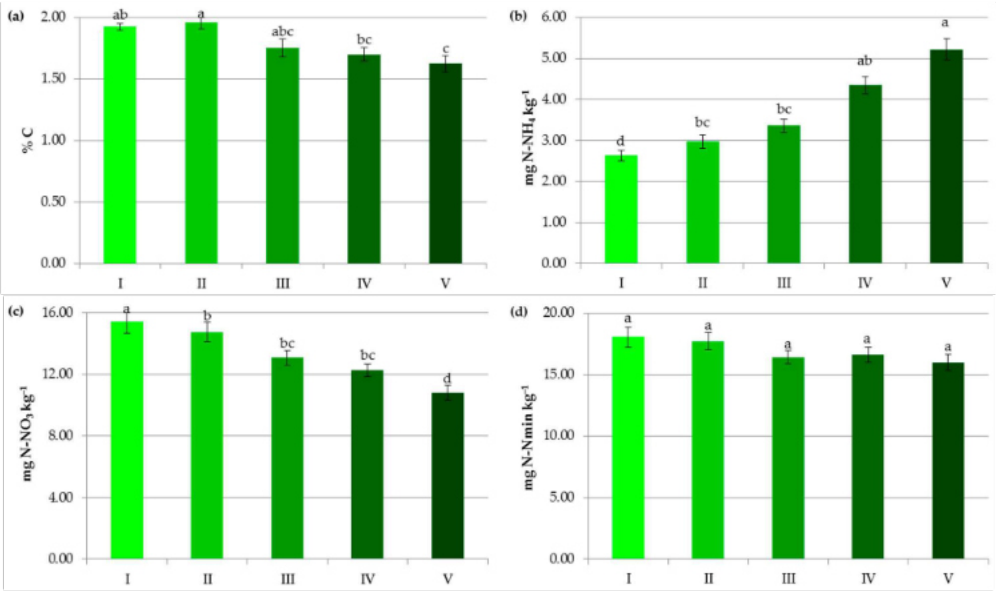

Figure 3. Impact of soil pH on contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**). I—alkaline soils, II—neutral soils, III—slightly acidic soils, IV—acidic soils, V—highly acidic soils. The same letter means not significantly different.

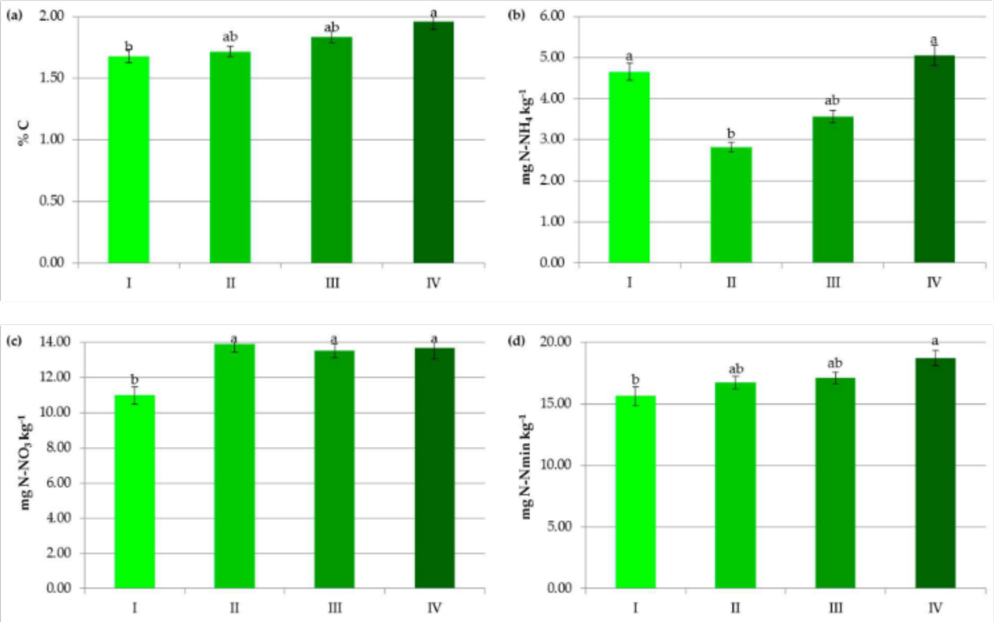

Figure 4. Impact of soil texture on contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**). Fractions smaller than 0.02 mm: I—<10%, II—10–20%, III—20–35%, IV—>35%. The same letter means not significantly different.

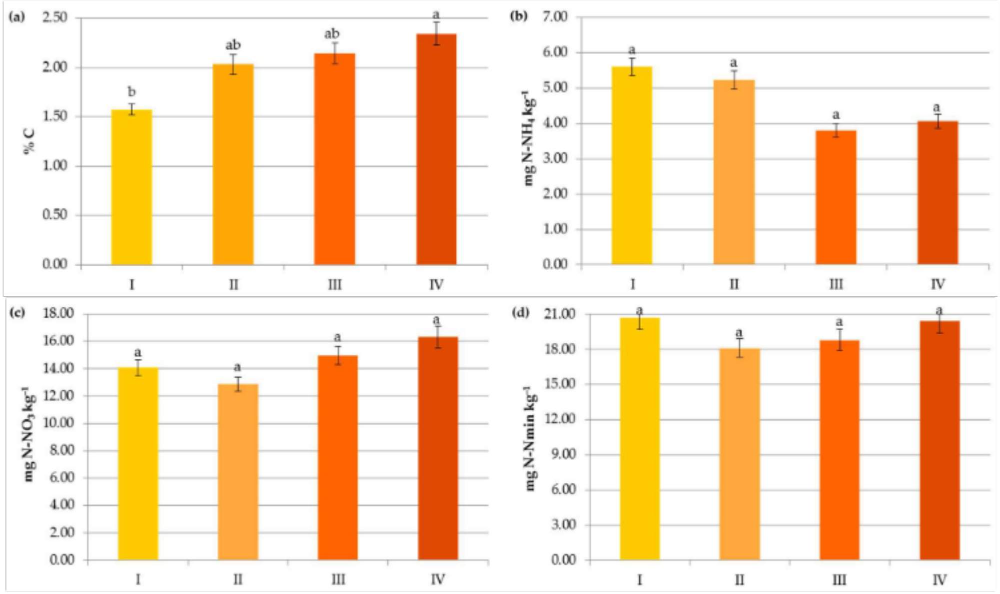

Figure 5. Impact of N manure application on contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**): I—<50 kg N ha^{-1}, II—50–100 kg N ha^{-1}, III—100–150 kg N ha^{-1}, IV—>150 kg N ha^{-1}. The same letter means not significantly different.

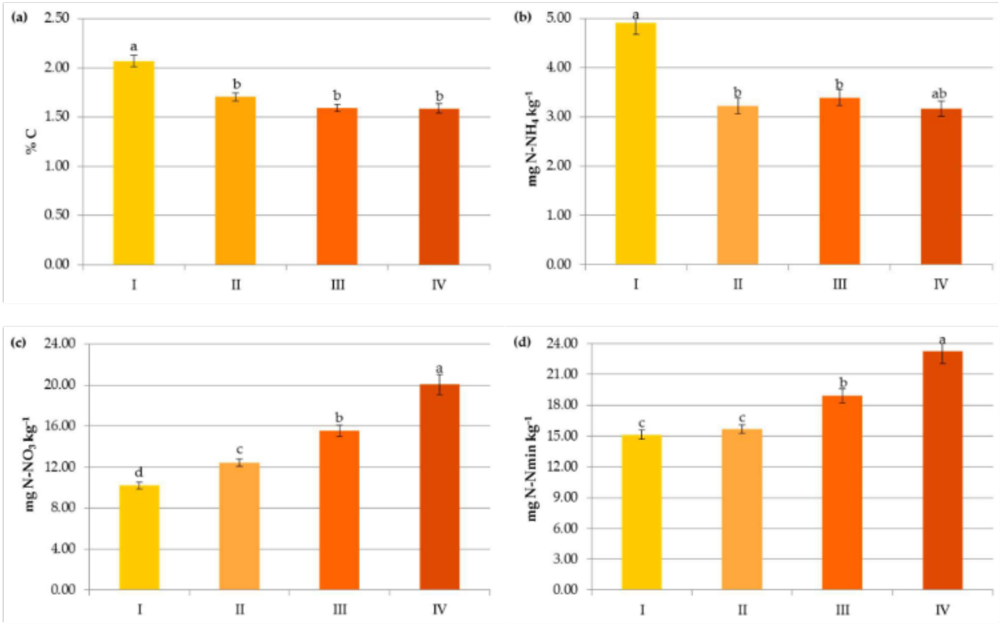

Figure 6. Impact of crop N fertilization on contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**): I—<50 kg N ha^{-1}, II—50–100 kg N ha^{-1}, III—100–150 kg N ha^{-1}, IV—>150 kg N ha^{-1}. The same letter means not significantly different.

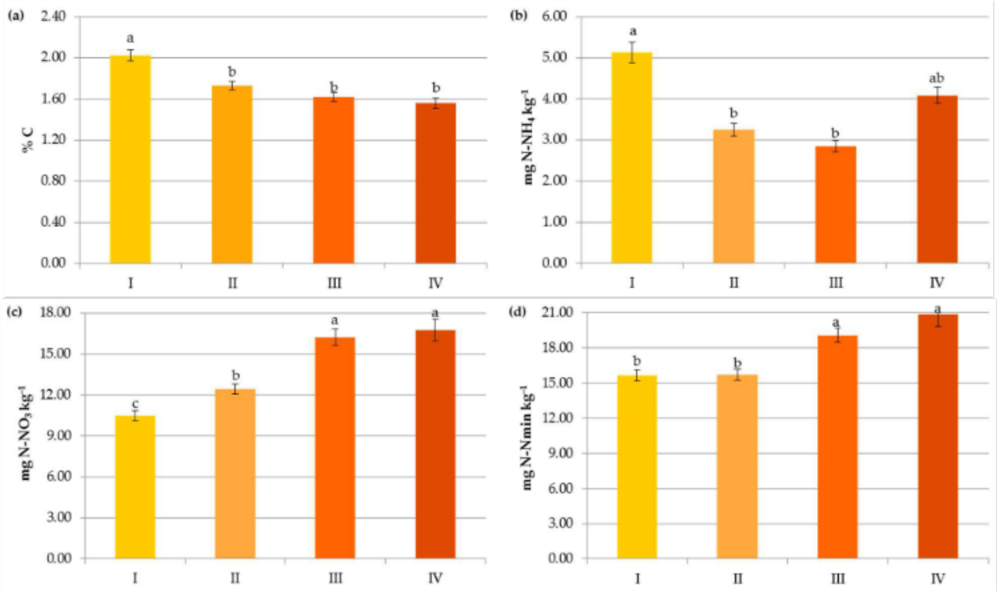

Figure 7. Impact of pre-crop N fertilization on contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**): I—<50 kg N ha^{-1}, II—50–100 kg N ha^{-1}, III—100–150 kg N ha^{-1}, IV—>150 kg N ha^{-1}. The same letter means not significantly different.

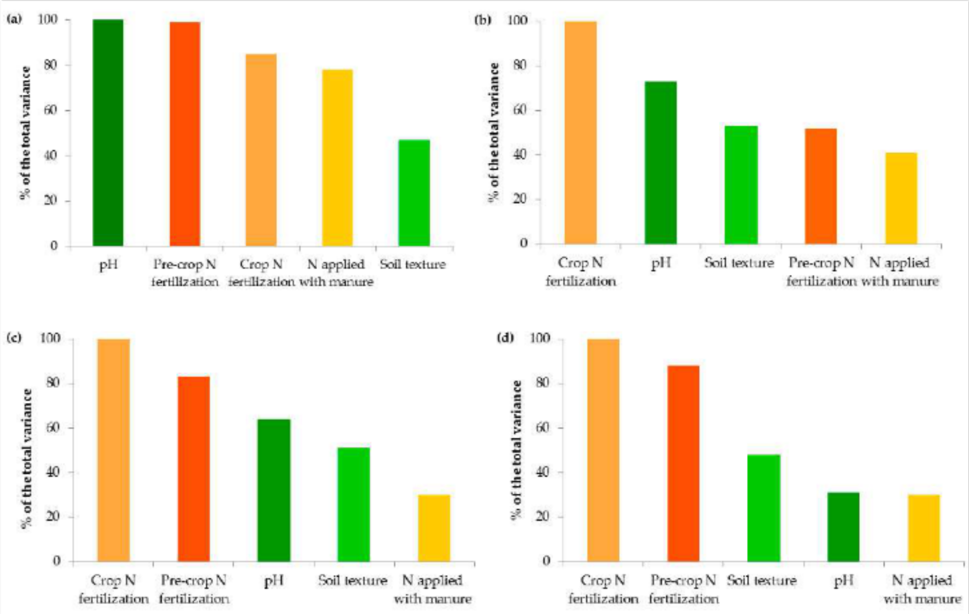

Figure 8. Variables in terms of their importance on the contents of organic carbon (**a**), ammonium nitrogen (**b**), nitrate nitrogen (**c**) and mineral nitrogen (**d**).

3.1. Soil Organic Carbon Contents

The average content of organic carbon in the studied soils was 1.78%. Soils with pH of 6.5–7.2 and above 7.2 accumulated the highest amounts of organic carbon, respectively 1.96% and 1.92%. This was in contrast to some research [27], which has demonstrated that alkaline soils are more prone to SOC losses than acidic ones due to the reduction in SOM complexation on mineral surfaces via ligand exchange. In the present study, a statistically significant decrease in the level of this parameter was observed in acidic and very acidic soils (Figure 3a). Solly et al. [28] also found that SOC content was lower in soils with pH < 5.5. Leifeld et al. [29] stated that the processes of carbon transformations in soils resemble strong pH dependencies, and their midpoints are reached at pH values between 4.3 and 5.3. A lot of authors [21,30,31] reported that low pH had a negative impact on SOM. In the present study, the identification of soil pH as the most important variable affecting SOC (Figure 8a) and a positive correlation between these parameters ($r = 0.947$) seem to confirm this thesis. Undoubtedly, these results were due to the influence of pH on the quantity and quality of the humus substances in the soil and the possibility of their stabilization. In the current research, the correlations of crop yields with pH and SOC were, respectively, $r = 0.886$ and $r = 0.759$. Apparently, higher pH optimized the plant growth environment, the use of macro- and microelements from soil reserves, and fertilizers, and stimulated biomass production [21,22]. The more significant the difference between the current pH value and the pH requirements of crops, the more liming contributes to increasing plant yields. It should be underlined that soil acidification limits biomass production and threatens the environment in Poland to a much greater extent than in many European and non-European countries. This is mainly due to the postglacial acidified parent material of Polish soils and the leaching of calcium and magnesium anions under the predominance of precipitation over evaporation, and a large share of light soils with high permeability in Poland [20,21]. According to some authors [22], greater inputs of post-harvest residues in limed soils compensate for initial carbon losses, caused by increased mineralization. Moreover, non-acid soils favor the transformation of humus substances into relatively stable organo-mineral complexes that are more difficult to decompose [21,32–34]. Lime, by releasing Ca^{2+} and Mg^{2+} ions and increasing the ionic strength of the soil solution, may enhance the flocculation of clay minerals and stimulate the activity of microorganisms secreting polysaccharides (binding agents). Thus, it contributes to the formation of stable soil aggregates, which improves the effectiveness of physical protection of organic matter. Calcium and magnesium ions and a higher pH also favor the transformation of humic substances to form calcium humates and other more complex organo-mineral compounds that are less prone to mineralization [21,35].

Soil texture was another factor significantly influencing the accumulation of soil organic carbon in the studied soils. However, its importance was lower in comparison to the soil pH (Figures 4a and 8a). The amount of SOC in heavy (fine) soils rich with clay and silt fractions was significantly higher than in other categories (Figure 4a). According to some authors [9,27,32,36], clay-rich soils have longer turnover times and slower decomposition of SOM than sandy ones. There are relationships, not only between clay contents but also their types and SOC level. Singh et al. [37] stated that the rate of SOM decomposition was greater in the kaolinitic-illitic clay minerals, followed by smectitic and allophanic. The greater SOC stabilization in the latter resulted from their higher specific surface area and/or proportion of micropores as well as a lower microbial activity. Our results were supported by Matus [38], who, based on a study of 1.5 million arable French soil samples, stated that 85% of the soil organic carbon content was sequestered in the <20 μm mineral fraction. Interestingly, the differences in the carbon content in soils containing <10% and 20–35% of fractions with a diameter below 0.02 mm did not exceed 10% (Figure 4a). This could be associated with the limited capacity of carbon stabilization. Frasier et al. [39] have demonstrated that if carbon inputs cannot be stabilized, as in the predominant number of analyzed soils, SOC remains in particulate forms, which are susceptible to mineralization. It should be noted that organic matter is stabilized in soils in two major ways: (i) by interactions with fine soil particles <20 μm, i.e., mineral components, via weaker (e.g., Van der Waals forces) or stronger bonds (e.g., ligand exchange), (ii) and by SOC incorporation within soil aggregates and physical protection of SOM inside them [8,11,27,39–41]. The first one is considered dominant [38].

In the present study, SOC content was significantly affected by organic and mineral fertilization (Figures 5–7). Its significant accumulation (2.34%) occurred when at least 150 kg N ha^{-1} in manure was applied. Undoubtedly, this result was due to the direct effect of the manure composition and the indirect impact of the increased crop growth and its residue in response to the additional nutrient supply [33,42]. Moreover, FYM, which was used in the analyzed agroecosystems, contains stabilized material that has already undergone the decomposition process [9], as well as a substantial amount of lignin and polyphenols and a high C:N ratio, which leads to the formation of stable complexes more resistant to oxidation [15,41].

In contrast to the manure inputs, a significant reduction, by 14.7–23.2%, in the content of SOC was observed with the increasing rate of crop and pre-crop N fertilization above 50 kg N ha^{-1} (Figures 6 and 7). Apparently, the acceleration of SOM mineralization through a lower C-to-N ratio [32,42,43], soil acidification [34], as well as negative changes in the stability of soil aggregates and/or in the microbial community [44] caused by the current and/or recent mineral fertilization prevailed on the amount of C accumulated in agricultural soils as a result of greater root exudates and increased biomass production, later returned to the soil as crop residues [33,44,45]. Some authors reported that N fertilizers enlarge carbon stocks only when crop straws were returned to soils [7,42,46] and their decline was observed under intensive cultivation and imbalanced fertilization [15]. Others [47] have stated that only manure inputs resulted in a significant enhancement of SOC in comparison to NPK treatments, and the crop residues had nothing to do with the increase in soil organic carbon after several years.

Interestingly, the variables analyzed in the study in terms of their importance on the organic carbon content can be ranked as follows: soil pH > pre-crop N fertilization > crop

N fertilization > N applied with manure > soil texture (Figure 8a). This indicates that the observed levels of organic carbon in the studied soils were mainly determined by the factors limiting SOC accumulation.

3.2. Mineral Nitrogen Contents

In the present study, organic matter contributed significantly to the availability of mineral nitrogen (N-NO_3 and N-NH_4) in the soils (Figure 9). The maximum content of N_{min} (18.24–18.31 mg kg^{-1}) was noted in soils containing above 2% of C (Figure 9c). These results are consistent with the findings of Ladha et al. [43] and Ren et al. [44] in which soil organic matter strongly influences soil N turnover and provides more than 50% of the nitrogen requirements of the crops. According to Soinne et al. [48], the amount of inorganic N available for plants is determined by net nitrogen mineralization, i.e., the difference between gross N mineralization and N immobilization in the microbial biomass. It should be noted that the contents of ammonium nitrogen were lower and more differentiated in carbon classes compared to nitrates (Figure 9a,b). These results may be explained by the fact that N-NH_4 and N-NO_3 have different biochemical characteristics (e.g., biological preference and ionic charge), and the former is adsorbed in exchangeable and non-exchangeable forms and nitrified as well as preferred by microorganisms due to the low energy cost [17,49–52].

The presence of nitrogen in the plant available pool was influenced by the same factors that govern SOM, but their importance was slightly different, e.g., both in the case of N-NH_4 and N-NO_3, mineral fertilization was the most important factor affecting their contents (Figure 8b–d). Interestingly, the pH and texture had less effect on the latter form of nitrogen (Figures 3 and 4).

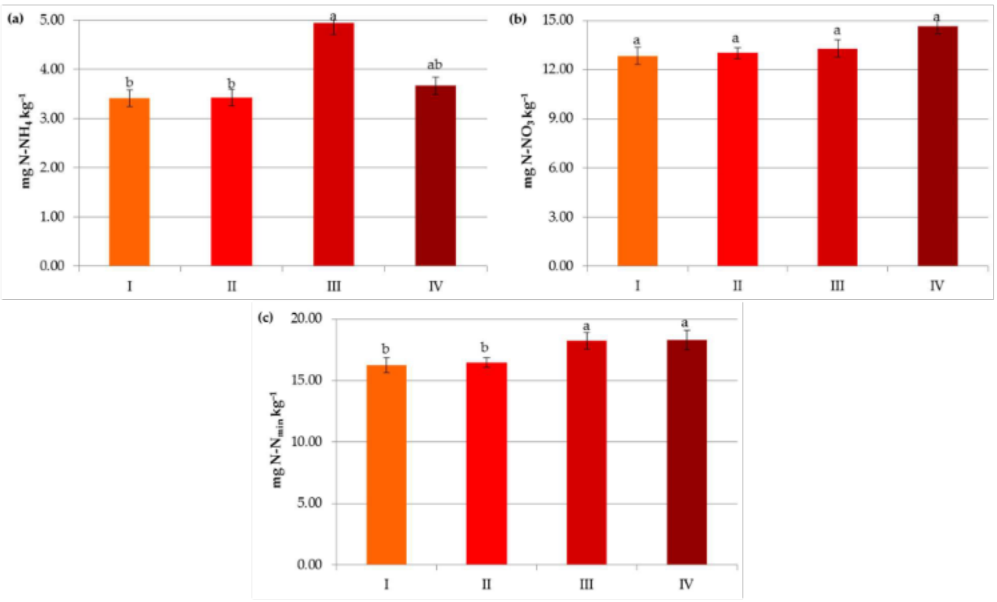

Figure 9. Impact of carbon level on contents of ammonium nitrogen (**a**), nitrate nitrogen (**b**) and mineral nitrogen (**c**): I—<1% C (very low), II—1–2% C (low), III—3–6% C (medium), IV—>6% C (high). The same letter means not significantly different.

In our research, the decline in soil pH was accompanied by a decrease in nitrate concentration (from 15.43 mg kg^{-1} at pH > 7.2 to 10.79 mg kg^{-1} at pH < 4.5) and an increase in NH_4^+ content (from 2.63 mg kg^{-1} at pH > 7.2 to 5.22 mg kg^{-1} at pH < 4.5) (Figure 3b,c).

The lower soil pH undoubtedly reduced the provision of substrate for nitrification and the rate of this process itself [50,53]. In some experiments, at $pH < 5.5$ ammonium cations produced from the SOM mineralization were accumulated in the soil profile [53] and alkaline conditions were beneficial for nitrification and elevation of the nitrate concentration in the soil solution [5]. It should be noted that higher soil pH greatly affects NO_3^- uptake by plants but is also likely to drive nitrate leaching and/or N loss by volatilization [5,51,52,54], which should be considered in N management decisions. Kemmit [55] even suggested that a combination of natural or human-induced soil acidification may be a useful mechanism to reduce nitrate leaching from some agroecosystems.

Our results were consistent with other findings [56,57] in which soil texture significantly influenced $N\text{-}NH_4$ and $N\text{-}NO_3$ pools (Figure 4b–d). The content of ammonium increased both in coarse- and fine-textured soils, indicating different processes that control it (Figure 4b). Soils rich in fine clay particles have a higher adsorption capacity for $N\text{-}NH_4$ [58] and usually contain more soil organic matter—a reservoir of ammonium cations. However, sandy soils are characterized by a faster mineralization rate and usually acidic conditions [56], limiting the biological oxidation of $N\text{-}NH_4$. The latter process also had an apparently predominant role in regulating the nitrate concentration, since its significantly lowest value (10.98 mg kg^{-1}) was reported in soils containing the smallest level of fine particle fractions (Figure 4c). Additionally, poorly structured sandy soils are prone to nitrate leaching losses due to faster water movement. Cameron et al. [59] cited data that gave an approximate ratio of leaching losses of 1:5 for a clay loam soil compared to a silt loam soil.

Changes in the N_{min} pool observed in the studied agricultural ecosystems, similarly to other studies [16,59], were mainly a result of the higher mineral N application rates in these systems (Figure 6). Interestingly, significant accumulation of nitrates occurred at a rate above 50 kg N ha^{-1} (12.43 mg kg^{-1}) and their concentration almost doubled after exceeding 150 kg N ha^{-1} (20.07 mg kg^{-1}), which might increase the risk of N losses due to leaching. In contrast to $N\text{-}NO_3$, the availability of ammonium declined by 34.35% when more than 50 kg N ha^{-1} was applied and remained constant with increasing doses of N (Figure 6). This was undoubtedly due to the N fluxes, i.e., mineralization, nitrification, denitrification, and volatilization, which are highly variable in response to mineral N input [7]. Similar dynamics of mineral nitrogen were observed in the case of pre-crop N fertilization (Figure 7). According to Cameron et al. [59], 15–25% of the N in applied mineral fertilizers remains in organic forms after harvest. Furthermore, the residual mineral N may be leached over the subsequent winter if excessive rates of nitrogen inputs are used.

Organic amendments did not significantly support mineral nitrogen contents in the present study (Figure 5). Most of the nitrogen in manured soils may be subjected to immobilization, and its transformation into mineral forms available to plants occurs in the long term, as reported by Christodoulou et al. [14].

4. Conclusions

In the environmental study, soil organic carbon levels were determined by the factors limiting its accumulation and contributed significantly to the availability of mineral nitrogen. The variables analyzed in the study in terms of their importance on the organic carbon content were ranked as follows: soil pH > pre-crop N fertilization > crop N fertilization > N applied with manure > soil texture. The presence of nitrogen in the plant available pool was influenced by the same factors that governed SOM, but their importance was slightly different, i.e., both in the case of $N\text{-}NH_4$ and $N\text{-}NO_3$, mineral fertilization was the most important variable affecting their contents. Carbon and nitrogen management strategy in agroecosystems should take into account the ranks of factors controlling their contents.

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Article

Selected Carbon and Nitrogen Compounds in a Maize Agroecosystem under the Use of Nitrogen Mineral Fertilizer, Farmyard Manure, Urease, and Nitrification Inhibitors

Monika Skowrońska [1,*], Sebastian Kuśmierz [2,*] and Jacek Walczak [3]

[1] Department of Agricultural and Environmental Chemistry, University of Life Sciences in Lublin, Akademicka 15, 20-950 Lublin, Poland
[2] Institute of Soil Science, Environment Engineering and Management, University of Life Sciences in Lublin, Leszczyńskiego 7, 20-069 Lublin, Poland
[3] Institute of Environmental Protection-National Research Institute, The National Centre for Emissions Management (KOBiZE), Słowicza 32, 02-170 Warsaw, Poland; jacek.walczak@kobize.pl
* Correspondence: monika.skowronska@up.lublin.pl (M.S.); sebastian.kusmierz@up.lublin.pl (S.K.)

Abstract: Carbon and nitrogen compounds in agroecosystems have attracted much attention in recent years due to their key roles in crop production and their impacts on environment quality and/or climate change. Since fertilization profoundly disrupted the C and N cycles, several mitigation and/or adaptation strategies, including the application of farmyard manure (FYM) and/or urease and nitrification inhibitors (UI and NI), have been developed. The aim of this study was to evaluate the contents of soil organic carbon and its fractions, the total and mineral forms of nitrogen, as well as CO_2 and N_2O emissions under mineral and organic fertilization with and without urease and nitrification inhibitors in a maize agroecosystem. A two-year field study was carried out on Cambisols (silt) in Poland. The experiment scheme included nine treatments: C (the control without fertilization), UAN (Urea Ammonium Nitrate), UAN+UI, UAN+NI, UAN+UI+NI, FYM with N mineral fertilizer base, FYM with N mineral fertilizer base+UI, FYM with N mineral fertilizer base+NI, and FYM with N mineral fertilizer base+UI+NI. It was found that treatments fertilized with cattle FYM were higher sinks and sources of C and N compounds in comparison to the UAN plots. The organic carbon, humic and humin acid, and total nitrogen concentrations, in contrast to ammonium and nitrate nitrogen, were not affected by the inhibitors added. Nitrification and urease inhibitors were effective in decreasing N_2O emissions only in treatments that were exclusively applied with UAN and had no significant influence on CO_2 emissions.

Keywords: UAN; FYM; urease inhibitor; nitrification inhibitor; CO_2 emission; N_2O emission; organic carbon; mineral nitrogen; humus fractions

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1. Introduction

Soil organic carbon (SOC) and nitrogen (N) in agricultural ecosystems have achieved tremendous attention over the past few decades due to their crucial roles in soil health maintenance, the efficiency of crop productivity, environmental quality, and/or climate change mitigation and adaptation [1].

Soil organic matter (SOM), which is critical to diverse soil functions and ecosystem services, represents the largest organic carbon reservoir in terrestrial ecosystems, which can accumulate 5–15% of the annual global C emissions mainly in humic substances (HS), which are classified according to their solubility into humins (insoluble at all pH conditions), humic acids (soluble in pH > 2), and fulvic acids (soluble at all pH values) [1,2]. Even small changes in SOC stocks may have a substantial effect on the atmospheric CO_2 concentrations [3]. It was reported that 25–29% of anthropogenic CO_2 emissions originate from agricultural soils. SOM also determines the amount of nitrogen in agroecosystems. Its microbiological decomposition results in the formation of mineral nitrogen–ammonium (NH_4-N) and nitrate (NO_3-N), which are available to plants but also easily subjected to losses via leaching, surface runoff, and volatilization [4,5]. These bring threats to the environmental quality, including the eutrophication and acidification of land and water ecosystems, ozone depletion, the formation of particulate matter, smog and acid rains, biodiversity loss, health problems, and effects on global warming [6,7]. Soil mineral forms of nitrogen can also be consumed by microorganisms and immobilized into organic forms. Approximately 833 kg of nitrogen is needed to sequester 10,000 kg of carbon in humus, assuming a C:N ratio of 12:1 [8].

The close connection of soil C and N cycling, driven mainly by the degradation and fixation of C and N, as well as nitrification and denitrification, means that even slight changes in their pools can have serious production and environmental consequences [9]. Agricultural practices, such as fertilization, have profoundly disrupted the C and N cycles [10]. The application of mineral and organic fertilizers into soil may lead to significant short-term changes in the organic matter cycling and acceleration of SOM mineralization or the immobilization of C and N. According to some authors, N mineral fertilizers initially intensify SOM mineralization; however, in the long-term period, due to increasing yields and crop residues, which can enhance carbon sequestration, they positively affect the SOC content. Some researchers, however, believe that one-sided mineral fertilization leads not only to the acceleration of mineralization processes and CO_2 emission, but also to the deterioration of humus quality [1,11]. Other studies indicate that mineral fertilizers in doses covering the fertilization needs of crops only prevent a decrease in the humus level [12].

Nitrogen fertilizer use aiming to replace microbially mediated N mineralization and supply this nutrient directly to crops [13] increases the content of total nitrogen and its mineral forms. This is caused by mineral N not being absorbed by the plants and the larger biomass of crop residues left in the field after harvesting. In contrast, organic fertilization providing SOC and nutrients such as N in agroecosystems can create a more tightly coupled cycle of C and N [13]. A meta-analysis based on 101 studies with a total of 592 treatments showed that the use of farmyard-(FYM), cattle-, and pig manure caused the highest SOM increases of 50%, 32%, and 41%, respectively [14]. If manure inputs were combined with N mineral fertilizers, the SOC accumulation was even greater. There are also studies showing no or adverse effects on SOM [15]. Therefore, according to some authors [14,15], there is a need for further research under local management and environmental conditions concerning the magnitude of change in SOC stocks as the result of manure application.

Organic inputs alter the soil organic carbon (SOC) dynamics affecting the chemical structure of soil organic matter. The identification of organic carbon sequestration in humic substances (HS) (humins and humic and fulvic acids) is crucial for understanding SOC stabilization and carbon cycling [16]. It is commonly believed that FYM fertilization increases the contents of humic acids and humins. However, some authors indicated the high susceptibility of the OM of soils treated with manure to oxidation, which may favor mineralization, leading to N losses.

Nitrogen and carbon inputs affect the emissions of CO_2 and N_2O [17]. Agroecosystems treated with mineral and organic fertilizers, however, have the potential to be not only sources but also sinks of CO_2 [18,19]. Nitrogen-containing fertilizers also boost the production of the most powerful long-lived greenhouse gas—N_2O—by providing a substrate for microbial denitrification, nitrification, and nitrifier denitrification processes, i.e., NO_3-N and NH_4-N [18,20,21]. A direct emission factor for N_2O from N inputs (mineral and organic) applied to soils is 0.01 kg N_2O-N/kg N input [22]. Several mitigation strategies have been developed to decrease the N emissions in agroecosystems, including the application of urease and/or nitrification inhibitors (UI and NI) [20,21,23,24]. NIs delay the bacterial oxidation of NH_4-N by depressing the activities of nitrifiers in soil, whereas UIs slow down the hydrolysis of urea to NH_4-N by preventing its binding to the enzyme urease [23,25]. UI and NI temporarily retard the microbiological transformations of nitrogen-based fertilizers, improving the synchronization of N bioavailability with plant uptake and mitigating N losses [25].

Previous studies indicated inconsistent or no impacts of inhibitors on CO_2 and N_2O emissions under maize cropping [20,21]. Recent research has combined UI with NI to increase the effectiveness in the reduction of N_2O emissions [21]. In Zaman's and Nguyen's experiment [26], the DIs (1:7 ratio w/w of UI and NI) were more effective in minimizing N losses. Chen et al. [27], after synthesizing data from 26 meta-analyses and reviews, stated that future research should focus on double inhibitors (DIs). There is also a lack of studies comprehensively examining the impacts of UI, NI, and/or DI inhibitors under organic and mineral fertilization on the quantity and quality of soil C and N compounds as well as CO_2 and N_2O emissions. We hypothesized that there were such relationships. Thus, the aim of this study was to evaluate the contents of soil organic carbon and its fractions, total and mineral forms of nitrogen, as well as CO_2 and N_2O emissions under mineral and organic fertilization with and without UI, NI, and DI.

2. Materials and Methods

2.1. Site Description and Experimental Design

A two-year field study was carried out in the 2020–2021 period in a randomized complete block design with three replicates at a farm situated in Piława Górna, Poland (50°66′74.73″ N, 16°76′47.16″ E) on Cambisols (silt) with a soil pH of 6.5, an SOC content of 10 g C kg^{-1}, a total nitrogen (TN) content of 1.11 g N kg^{-1}, and a CEC of 11.28 cm(+) kg^{-1}. The test plant was maize, specifically the SY Talisman variety (FAO 220–230). The annual precipitation was 589.0 mm and 603 mm in the first and second years of the experiment, respectively. Average monthly temperatures in January and July were −1.2 °C and 19.4 °C and −1 °C and 20.0 °C, respectively. Each treatment plot had dimensions of 13.5 m in width × 13.5 m in length. The experiment scheme included nine treatments (Table 1).

Table 1. Experimental treatments.

Treatment	Mineral N Fertilization	Organic Fertilization	Inhibitor
C	–	–	–
UAN	UAN (150 kg N ha^{-1})	–	–
UAN+UI	UAN (150 kg N ha^{-1})	–	NBPT *
UAN+NI	UAN (150 kg N ha^{-1})	–	DMPP *
UAN+UI+NI	UAN (150 kg N ha^{-1})	–	NBPT+DMPP *
FYM	UAN (150 kg N ha^{-1})	Cattle FYM (129 kg N ha^{-1})	–
FYM+UI	UAN (150 kg N ha^{-1})	Cattle FYM (129 kg N ha^{-1})	NBPT **
FYM+NI	UAN (150 kg N ha^{-1})	Cattle FYM (129 kg N ha^{-1})	DMPP **
FYM+UI+NI	UAN (150 kg N ha^{-1})	Cattle FYM (129 kg N ha^{-1})	NBPT+DMPP **

Notes: C—the control without fertilization; UAN—urea ammonium nitrate; FYM—farmyard manure; UI—urease inhibitor; NI—nitrification inhibitor; NBPT—*N*-(*n*-butyl) thiophosphoric triamide; DMPP—3,4-dimethylpyrazole phosphate; *—the inhibitor applied with the mineral fertilizer; **—the inhibitor applied with the organic fertilizer.

2.2. Soil Sampling and Analysis

Soil samples (25 per plot) were collected before the beginning of the experiment and at the end of each growing season. Soil samples were air-dried, homogenized, and sieved (2 mm sieve-mesh). The soil samples for NH_4-N and NO_3-N analysis were placed in polyethylene bags and stored in the refrigerator. In air-dried soil samples, the following parameters were determined: soil organic carbon by sulfochromic oxidation with titration of excess $K_2Cr_2O_7$ with $FeSO_4(NH_4)_2SO_4 \cdot 6H_2O$, total nitrogen according to the Kjeldahl method, and particle size distribution using the laser diffraction method (LDM) based on the light intensity distribution pattern of the scattered light emitted from that particle group [28]. The isolation of HA, FA, and H from soil samples were carried out according to the Schnitzer method [29].

Mineral nitrogen content was determined using Skalar SAN plus Segmented Flow Analyzer (Skalar Analytic B.V., De Breda, The Netherlands) after extraction with 1% of

K_2SO_4 [28]. The data are presented in this paper in the form of the means of the two years of studies.

2.3. CO_2 and N_2O Measurements

Soil CO_2 and N_2O emissions were measured (30 measurements per year) in situ using a portable FTIR analyzer model, GT5000 Terra (Gasmet Technologies Oy, Vantaa, Finland), equipped with the device chamber. The soil CO_2 and N_2O emissions were measured at randomly selected locations in each experimental plot between 11 am and 1 pm to eliminate the diurnal variability. The results were extrapolated to 24 h and 1 ha. The data were presented in the paper in the form of the means of the two years of studies.

2.4. Statistical Analysis

The statistical analysis of the results was performed using Statistica 13.3. A one-way analysis of variance (ANOVA) and Tukey's mean separation were used to determine the statistical significance at $p < 0.05$. Pearson's linear correlation coefficient was calculated with a significance level of $p < 0.05$.

3. Results and Discussion

Mineral and organic fertilization, as well as the use of nitrification and urease inhibitors, caused quantitative and qualitative changes in the contents of carbon and nitrogen compounds in the maize agroecosystem. It is worth noting that, in the experiment conducted, the largest statistically significant differences were observed in the nitrogen pool under the conditions of mineral fertilization and the application of urease and nitrification inhibitors. The weaker effects of UI and NI under organic fertilization may have indicated the occurrence of their adsorption, faster degradation, and effectiveness reduction at higher SOC contents [25].

3.1. Soil Organic Carbon and Total Nitrogen in the Soil

Significantly higher contents of SOC (11.28 g kg^{-1}) and TN (1.40 g kg^{-1}) were found in the soil applied with farmyard manure combined with mineral fertilizer compared to the unfertilized control (Figures 1 and 2), suggesting that organic and mineral fertilization had a beneficial effect on these parameters. Several authors also reported that the SOC levels increase in treatments with farmyard manure [17,30,31] and/or with N inorganic fertilizers [30,32]. This was linked to the amount of additional C and N applied with fertilizers and/or improvements in the crop yields and higher C and N input via rhizodeposition and plant residues [30,33]. In the present study, urease and nitrification inhibitors did not have a significant effect on the SOC and TN concentrations (Figures 1 and 2). The SOC/TN ratios were low (below 10; Figure 3).

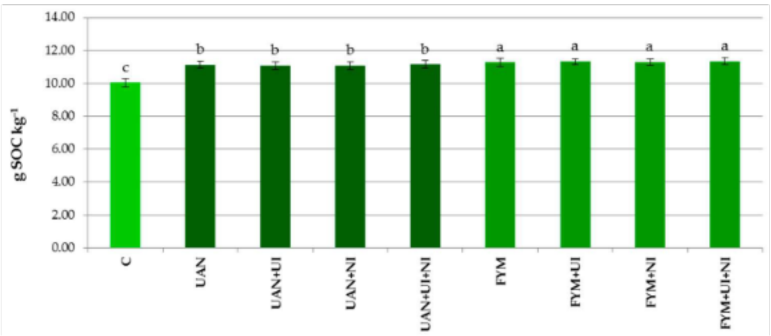

Figure 1. Soil organic carbon (SOC) content. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

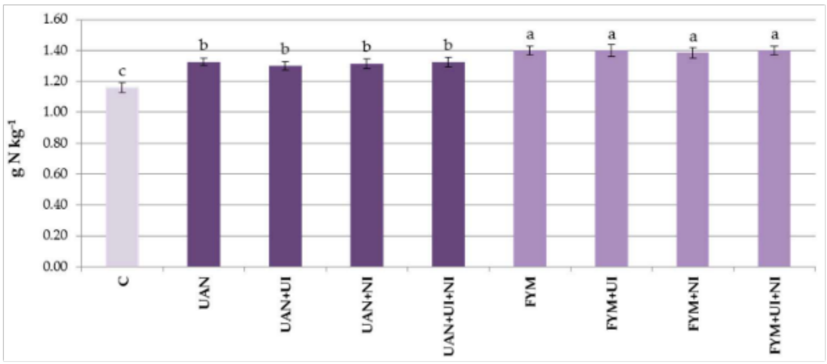

Figure 2. Total nitrogen (TN) content. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

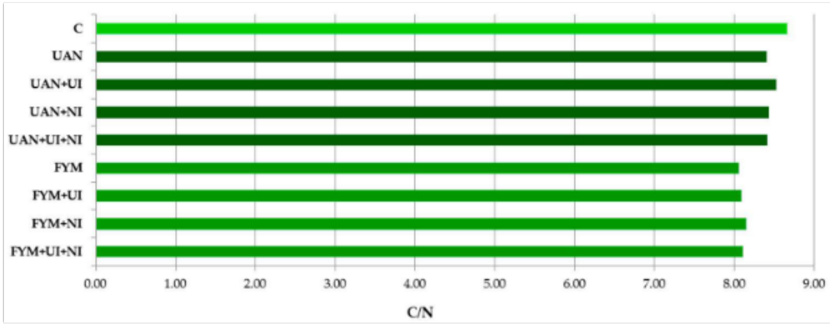

Figure 3. SOC/TN ratios. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

3.2. Humus Fractions in the Soil

In the present study, the SOM content fluctuations were accompanied by changes in the fractional composition of the humus. Our results showed significant quantitative differences between the major components of the soil organic matter, i.e., humic substances (HS). The HS fractions in the soils tested were dominated by C-HA (2.21–2.62 g kg^{-1}) and C-H (5.42–6.22 g kg^{-1}), which is consistent with the previous research [34]. Organic and mineral-amended plots registered higher C-FA, C-HA, and C-H contents compared to the control treatment (Figures 4–6). However, significant differences in impact between organic and mineral fertilization were found only in the case of the C-HA and C-H concentrations. According to some authors [34,35], OM application into soil favored HA formation mainly from FAs during the inception phase of the humification process.

The ratios between C-HA and C-FA expressed as a humification index (HI), indicating the intensity of humification [34,36] were higher in the soils of the FYM treatments (1.10–1.12) than in the plots with UAN (1.0–1.04) (Figure 7). According to some authors [35], HI values > 1 showed longer residence periods for the humic acid fraction in soils. In the present study, urease and nitrification inhibitors did not have significant impacts on the HS fractions (Figures 4–6).

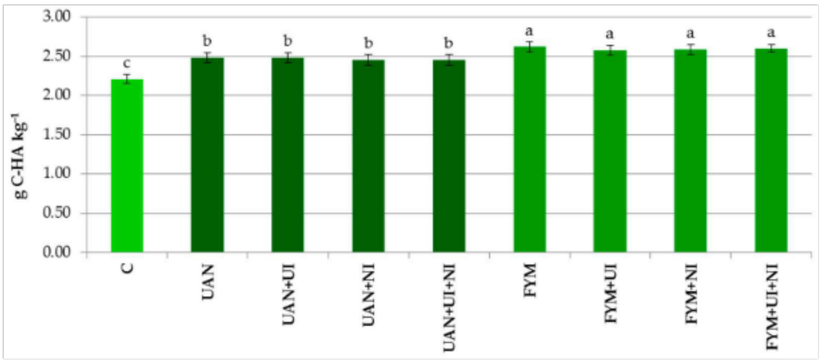

Figure 4. Content of humic acids (C-HA). The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

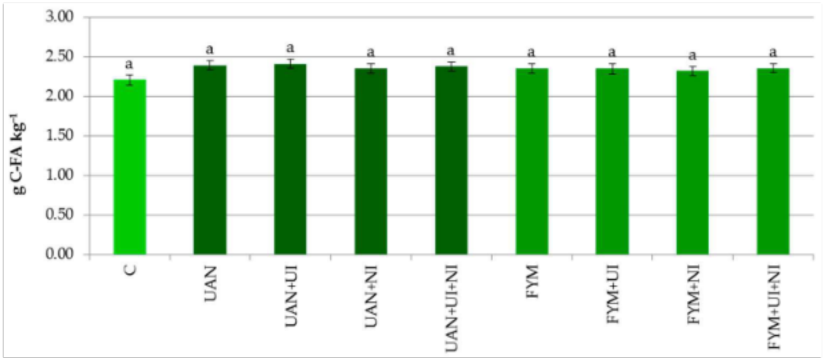

Figure 5. Content of fulvic acids (C-FA). The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

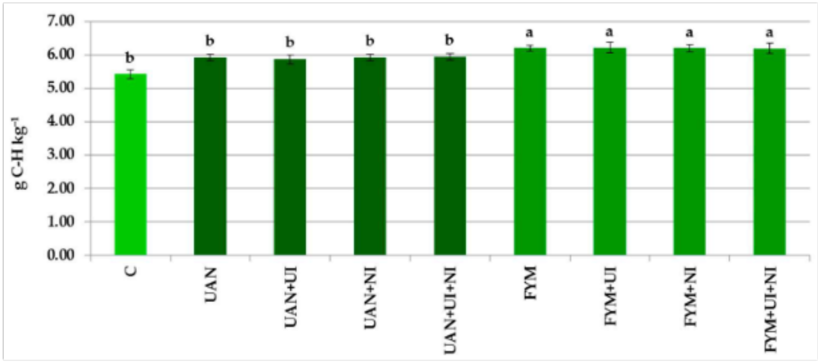

Figure 6. Content of humins (C-H). The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

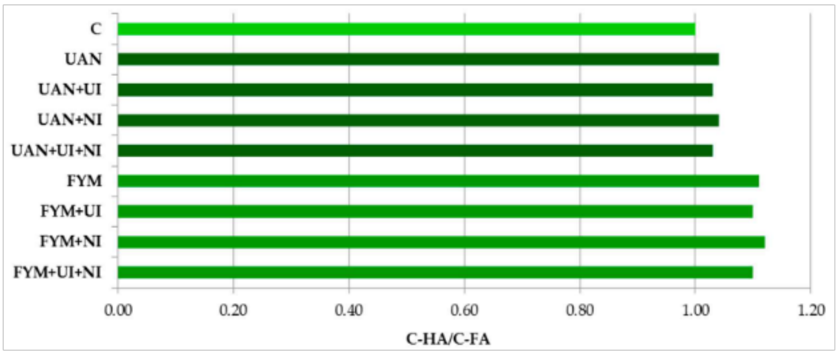

Figure 7. Humification index (HI). C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

3.3. Mineral Nitrogen in the Soil

The transformations of nitrogen in the soil are mainly determined by mineralization, immobilization, oxidation, and reduction. Two of the key compounds in these processes are ammonium and nitrate ions.

In our research, the FYM treatment had the highest NO_3-N and NH_4-N contents, respectively, which were 7.70–8.01 mg kg^{-1} and 3.15–3.24 mg kg^{-1} (Figures 8 and 9). Several authors also noticed that a combination of organic and inorganic fertilizers plays a significant role in the improvement of N bioavailability in soils [37–39]. The mineral nitrogen concentrations rose considerably under FYM application with an increasing N rate to $\geq$80 kg N·ha^{-1} in 0–15 cm and to 120 kg N·ha^{-1} in 15–60 cm depths [40].

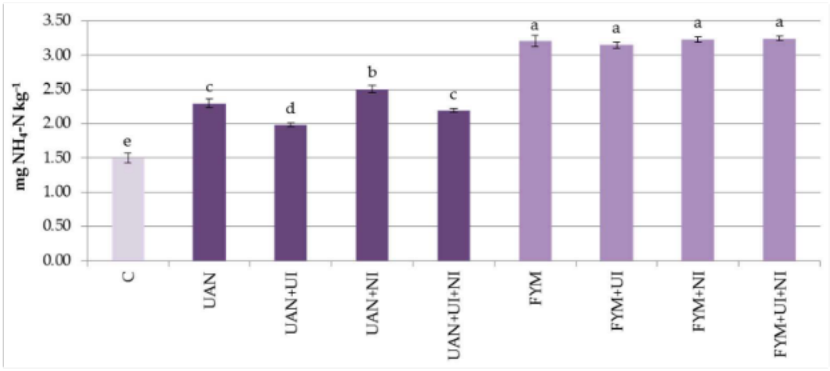

Figure 8. Ammonium content (NH_4-N) in the soil. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

In the present study, the inhibitor addition (NBPT, DMPP, DI) decreased the soil NO_3-N content compared to the soil with applied FYM (Figure 9). However, this reduction was not statistically significant. There were also no significant effects of inhibitor use with farmyard manure on the NH_4-N concentrations, although the treatments with nitrification and double inhibitors had numerically greater contents than the FYM and FYM+UI treatments.

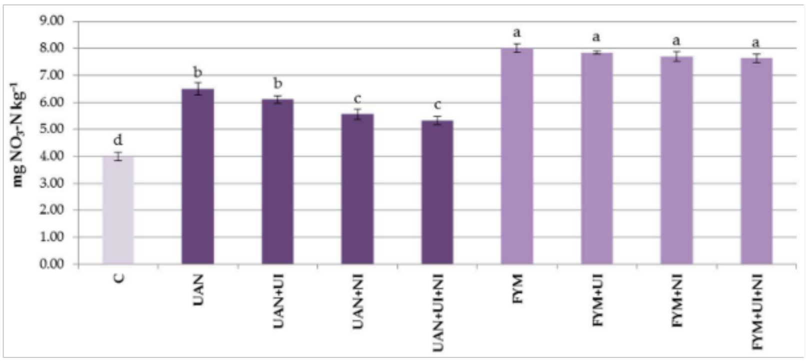

Figure 9. Nitrate content (NO_3-N) in the soil. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

The addition of DMPP with the UAN fertilizer effectively decreased the nitrification rates in the soil, raised the content of NH_4-N by 8.70%, and lowered the NO_3-N concentration by 14.46% (Figures 8 and 9), which is consistent with the results of other studies [7,24,41]. DMPP extends the residence time of NH_4-N in soils due to the deactivation of the enzyme responsible for the first step of nitrification, i.e., the oxidation of NH_4^+ to NH_2OH via indiscriminate binding and suppressing ammonium monooxygenase activity [23–25,41–43]. Abalos et al. [44] noticed that NI applications could diminish denitrification-induced N losses by decreasing the soil NO_3-N contents for denitrification, which allows the available nitrogen to be retained in the soil and become absorbed by the plants for a longer time.

In the present study, the application of NBPT with mineral fertilizer led to a decrease in the contents of both mineral forms of nitrogen (Figures 8 and 9). N-(n-butyl)thiophosphoric triamide is quickly converted to its more effective O analog, N-(n-butyl)phosphoric triamide, which forms a tridentate ligand with the urease enzyme to slow down the catalytic hydrolysis of urea to NH_4^+ [25,45]. As a result of these processes, NH_4^+ is gradually produced, which enables its more efficient uptake by plants and, at the same time, reducing the extent of nitrification and the potential loss of NO_3-N [25,42].

In previous studies [43], mineral fertilization with NI and UI inhibited not only nitrification but also urea hydrolysis, which resulted in significant decreases in the NO_3-N and NH_4-N concentrations, which was observed in the present experiment in the case of the latter (Figures 8 and 9).

3.4. CO_2 and N_2O Emissions

In the conducted experiment, changes were observed not only in the pool of soil carbon and nitrogen but also in the emissions of their gaseous compounds, i.e., CO_2 and N_2O.

The carbon dioxide emissions ranged between 100 and 125 kg CO_2 ha^{-1} d^{-1} (Figure 10). The control treatment showed the lowest CO_2 losses, and the application of UAN did not induce significant changes in the CO_2 emissions in comparison to the unfertilized treatment, which was consistent with other authors' research [46,47]. The addition of DMPP and NBPT with the UAN had no significant impact on CO_2 efflux (Figure 10).

Previous studies showed contradictory effects of UI and NI on CO_2 fluxes. Zhang et al. [48] noticed a decrease in CO_2 emissions following the use of DMPP with mineral fertilizers in field experiments. Other authors reported that the application of NBPT together with nitrification inhibitors in wheat fields mitigated soil CO_2 release by blocking soil carbon mineralization. Huéfrano et al. [46] and Wang et al. [49] observed that CO_2 emissions were not affected by inhibitors. Zhang et al. [48] reported that CO_2 efflux from a clay loam grassland was unaffected by DMPP addition. The discrepancy observed in the inhibitory impact on the soil CO_2 emission may partially lie in the differences in soil physicochemical properties (pH, Eh, and clay content) [48].

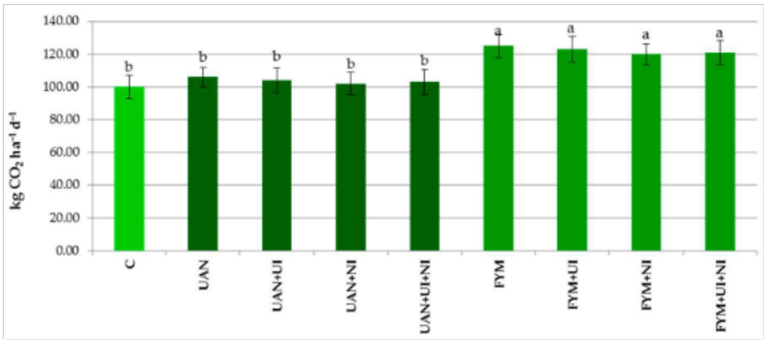

Figure 10. CO_2 emission in a maize agroecosystem. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

Since CO_2 emission is closely linked with the decomposition of organic matter [48,50], the cattle manure treatments significantly stimulated the soil CO_2 emissions by 17.92% and 25%, respectively, in comparison to the UAN and C plots (Figure 10). Sistani et al. [47] also stated that animal manure applied in farmland may be beneficial to soil health. However, it can also increase the production of GHG. Several authors reported [17,30] that carbon dioxide emissions are greater from soils treated with manure compared to inorganic fertilizer, which was attributed to a greater OM availability for microbial respiration in soil. According to previous studies, the soil C/N ratio plays a key role in controlling CO_2 emissions [17], which is consistent with our study. The low SOC/TN ratios in our experiment imply that a prevailing decomposition of OM resulted in significantly higher CO_2 emissions in the treatments characterized by lower values of this parameter (FYM, FYM+UI, FYM+NI, and FYM+UI+NI treatments; Figures 3 and 10; $r = -0.963$). Abdalla et al. [30] reported that organic fertilization enhances microbial growth and activities, resulting in accelerated SOM mineralization and a priming effect. It should be underlined that, in the present study, despite the greater SOM mineralization in the FYM treatments, the final SOC level was still significantly higher in comparison to the mineral-fertilized plots (Figure 1). Significant correlations were noticed between CO_2 emissions and concentrations of SOC ($r = 0.622$), TN ($r = 0.794$), C-HA ($r = 0.833$), C-H ($r = 0.844$), NH_4-N ($r = 0.921$), and NO_3-N ($r = 0.932$) (Table 2). Other authors reported earlier that the availability of N and SOM quality are the key factors to C mineralization in soils [17,34].

Table 2. Correlation coefficients between determined soils' parameters.

Parameter	**SOC**	**TN**	**C-HA**	**C-FA**	**C-H**	**NH_4-N**	**NO_3-N**	**CO_2**	**N_2O**
SOC		0.930 ***	0.935 ***	0.750 ***	0.914 ***	0.790 ***	0.818 ***	0.622 ***	0.786 ***
TN	0.930 ***		0.948 ***	0.529 ***	0.942 ***	0.913 ***	0.908 ***	0.794 ***	0.884 ***
C-HA	0.935 ***	0.948 ***		0.585 ***	0.965 ***	0.904 ***	0.947 ***	0.833 ***	0.931 ***
C-FA	0.750 ***	0.529 ***	0.585 ***		ns	ns	ns	ns	ns
C-H	0.914 ***	0.942 ***	0.965 ***	ns		0.930 ***	0.918 ***	0.844 ***	0.907 ***
NH_4-N	0.790 ***	0.913 ***	0.904 ***	ns	0.930 ***		0.929 ***	0.921 ***	0.924 ***
NO_3-N	0.818 ***	0.908 ***	0.947 ***	ns	0.918 ***	0.929 ***		0.932 ***	0.987 ***
CO_2	0.622 ***	0.794 ***	0.833 ***	ns	0.84 ***4	0.921 ***	0.932 ***		0.936 ***
N_2O	0.786 ***	0.884 ***	0.931 ***	ns	0.907 ***	0.924 ***	0.987 ***	0.936 ***	

Notes: *** $p < 0.001$; ns—not significant.

Changes in N_2O emissions significantly depended on the fertilization used. The highest flux rate (5.68 g ha^{-1} day^{-1}) was observed for the FYM treatment, while the lowest one was found in the control treatment (Figure 11). This was consistent with other studies where organic fertilization increased N_2O emissions [38,51,52], and this might be explained by two crucial mechanisms. Firstly, the total nitrogen input was higher in the FYM treatments. Several researchers reported that the amount of N_2O emissions rose strongly when the N rate was higher than 90 kg N ha^{-1}–200 kg N ha^{-1} [20]. According to some authors [45], the N_2O emission flux increased exponentially with a nitrogen rate of 0–225 kg N ha^{-1}. A positive correlation was also observed between N application rates and N-N_2O emissions [45,51]. Secondly, FYM provides a source of readily available C, which could stimulate nitrifying and denitrifying bacteria and N_2O production in soils [40,51,52]. The growth of active microorganisms and O_2 consumption in soil pores may result in the formation of a micro-anaerobic environment, favoring denitrification and N-N_2O production [51]. Cai et al. [45] stated that, under conditions with limited O_2, nitrous oxide may be produced via nitrifier denitrification or nitrification-coupled denitrification, and under highly anaerobic conditions, its production is dominated by denitrification.

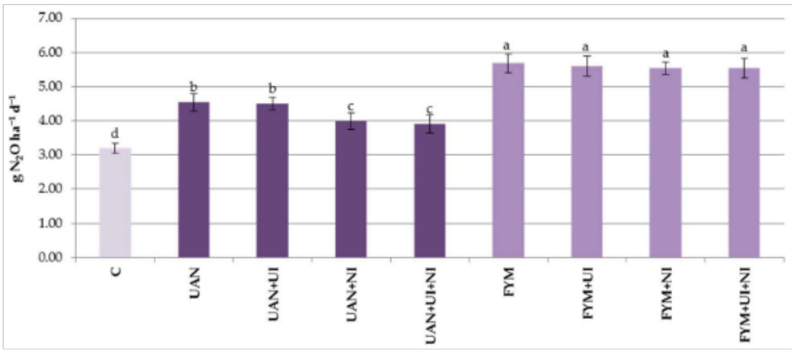

Figure 11. N_2O emissions in a maize agroecosystem. The same letter means not significantly different. C—control without fertilization; UAN—urea ammonium nitrate; UI—urease inhibitor; NI—nitrification inhibitor; FYM—farmyard manure with N mineral fertilizer base.

In the present study, the application of urease, nitrification, and double inhibitors with organic fertilizer did not significantly affect the N_2O emissions, which were within the range of 5.54–5.59 g ha^{-1} day^{-1} (Figure 11). Other studies also did not report an impact of UI, NI, and DI added to manure regarding the reduction in nitrous oxide emissions [53], which was due to the gradual release of mineral forms of nitrogen from FYM and the absorption or increasing decomposition of inhibitors in the presence of higher organic C concentrations [53,54].

Compared with the UAN treatment, the use of DMPP and NBPT+DMPP significantly decreased the N_2O emissions by 11.89% and 13.88%, respectively (Figure 11). This was in line with studies by other authors [20], who noticed that the application of nitrification inhibitors reduced the soil N_2O emissions by 1.8–61.0%. Cui et al. [7] and Ma et al. [41] reported that DMPP with urea-based fertilizers significantly inhibited the potential of the nitrification rate since it is characterized by low mobility, slow biodegradation, and persistence in the soil environment as well as interactions with ammonium monooxygenase to suppress the first rate-limiting step of soil nitrification.

The results of the current research indicate that the addition of NBPT to the mineral fertilizer decreased the value of the N_2O emissions, but the reduction was not significant. Urease inhibitors, such as NBPT, influence the conversion of amide nitrogen to ammonium nitrogen during urea hydrolysis. Hence, they could retard the N-NH_4 supply, which decreases the substrate availability for both nitrification and subsequent denitrification, i.e., the main processes of N_2O production [20,43]. According to the data in the literature [25,42], although NBPT may delay urea hydrolysis for 3–15 days, depending on environmental factors, its influence on N_2O emissions is highly variable, ranging from no effect to reduced or even increased emissions of nitrous oxide. The relatively low N_2O reductions under the inhibitor used in the conducted experiment could be the result of the high contents of clay and silt in the soil tested. According to some authors, NBPT and DMPP applications were more effective in depleting N_2O emissions in coarse than in fine soil due to the larger adsorption of inhibitors by clays in the latter [25,41].

There were positive correlations between the emission of N_2O and concentrations of SOC (r = 0.786), TN (r = 0.884), C-HA (r = 0.931), C-H (r = 0.907), NH_4-N (r = 0.924), and NO_3-N (r = 0.987) (Table 2), which is consistent with other studies [17,53,55]. The high correlation between N_2O emission and NH_4-N concentration in the tested soil confirms that nitrification can be an important source of N_2O [32,45]. The soil mineral N content is regarded as one of the key drivers of N_2O emissions since ammonium and nitrate serve as sources for nitrification and denitrification, respectively, which are processes that produce nitrous oxide [49,55]. Some authors [53] reported that the NO_3^- intensity explained 80–90% of the variability in N_2O emissions. In the present experiment, more than 97.48% and 85.35% of the variability in N_2O emissions may be explained by the regression equation, in which the explanatory variables are NO_3-N and NH_4-N, respectively (Figures 12 and 13). According to some authors [55], NH_4-N enhances soil N_2O emission only at a lower soil moisture.

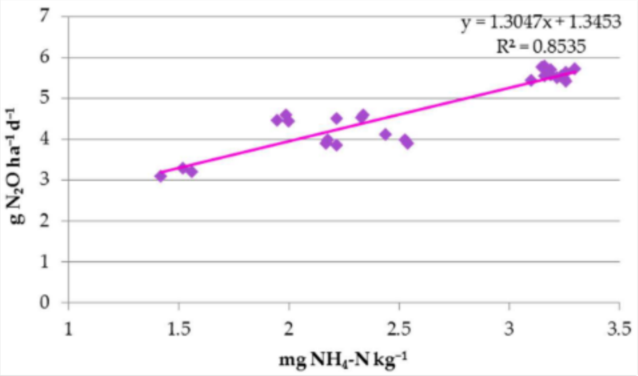

Figure 12. The relationship between N_2O emissions and NH_4-N contents in the soil.

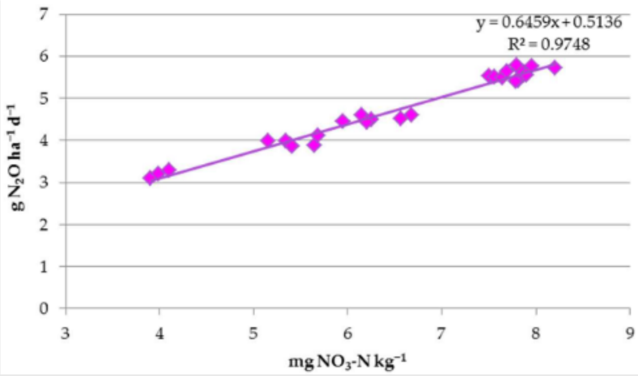

Figure 13. The relationship between N_2O emissions and NO_3-N contents in the soil.

It should be kept in mind that agronomic treatments impact GHG efflux differently, and relationships between CO_2 and N_2O emissions and soil properties are not universal [17].

4. Conclusions

The treatments that included fertilization with farmyard manure were higher sinks and sources of carbon and nitrogen compounds compared to the UAN plots. Despite the significant increases in CO_2 and N_2O emissions in organic fertilized soils, the final levels of soil organic carbon, humic acids, humins, total nitrogen, ammonium, and nitrate nitrogen were still significantly higher in comparison to the mineral-fertilized ones. Nitrification and double inhibitors were effective in decreasing N_2O emissions only in treatments that exclusively applied UAN and had no impact on the CO_2 efflux. In the present study, the soil organic carbon, humic acid, humin, and total nitrogen concentrations, in contrast to the NH_4-N and NO_3-N contents, were not affected by the inhibitors added. The analyzed soil parameters were positively correlated with CO_2 and N_2O emissions, indicating their contributions to the processes of soil respiration, nitrification, and denitrification. Further, longer-lasting studies on quantitative and qualitative changes in the contents of carbon and nitrogen compounds in agroecosystems under mineral and organic fertilization, as well as the use of nitrification and urease inhibitors, are recommended under different climate and soil conditions.

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Department of Environmental and Agricultural Chemistry, Faculty of Agrobioengineering,
University of Life Sciences in Lublin, Akademicka 13, 20-400 Lublin, Poland
* e-mail: sebastian.kusmierz@up.lublin.pl

SEBASTIAN KUŚMIERZ, MONIKA SKOWROŃSKA

Carbon farming and nutrient management. Influential factors of Polish farmers' perception of pro-climate measures

Rolnictwo węglowe i zarządzanie składnikami pokarmowymi. Czynniki warunkujące postrzeganie przez polskich rolników działań proklimatycznych

Abstract. Carbon farming and nutrient management, a sustainable pro-environmental and pro-climate approach to enhance soil quality and mitigate carbon losses, faces implementation challenges in the European Union. To explore potentially existing barriers, a survey involved 122 Polish farmers, representing diverse systems and land-use. Utilizing structured questionnaires, in-depth interviews, and Principal Component Analysis, we assessed farmers' perceptions of six pro-environmental and pro-climate measures. The survey highlighted factors influencing farmers' willingness to adopt surveyed practices, revealing that the potential to enhance soil carbon and nitrogen stocks outweighed the impact of subsidies, bureaucracy, age, and farm size. Barriers included technical challenges and machinery limitations, notably hindering manure and slurry incorporation. Conservation tillage was considered least feasible nationally, attributed to machinery needs and a preference for conventional practices. Addressing these challenges, especially in conservation tillage, requires targeted education. Raising awareness about measures' impact on soil carbon stock emerged as a potent means to overcome identified barriers.

Key words: carbon farming, individual in-depth interviews (IDI), structured questionnaire, sustainable agriculture

INTRODUCTION

Environmental and climatic threats related to agricultural production have become pivotal factors in determining the direction of agricultural development and agroecosys-

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tem protection in the European Union (EU) [Walczak et al. 2022]. This has been reflected in the subsequent reforms of the EU's agricultural policy. The recent stage, initiated by the European Green Deal strategy, mandates EU farmers to reduce their carbon footprints and adopt more sustainable practices [European Commission 2021, Faichuk et al. 2022, Wrzaszcz 2023].

These issues played a significant role in the development of the national (Polish) Strategic Plan for the Common Agricultural Policy for 2023–2027 [Dz.U.2023.412], which introduced eco-schemes [Latacz-Lohmann et al. 2022, Runge et al. 2022, Jongeneel and Gonzalez-Martinez 2023). The most extensive and frequently used eco-scheme by Polish farmers is "carbon farming and nutrient management", encompassing both CO_2 sequestration and protecting the soil by increasing its ability to retain nutrients [Styburski et al. 2023]. By engaging farmers in the pursuit of additional environmental and climate objectives, carbon farming and low-emission practices aim to contribute to environmental protection and sustainable agriculture, thereby enhancing agricultural efficiency while mitigating anthropogenic pressures arising from agricultural activities. Consistent with the scenarios evaluated by the Intergovernmental Panel on Climate Change (IPCC), the European Commission, as articulated in the Circular Economy Action Plan 3 released in March 2020, has declared its intention to formulate a robust certification framework [European Commission 2020]. This framework aims to facilitate the certification of carbon removals, serving as a strategic instrument to stimulate the adoption of carbon removal practices and enhance the circularity of carbon cycles [European Commission 2022].

The objectives of the selected carbon farming measures addressed in this study encompass various key pro-environmental and pro-climate actions, including biodiversity protection, soil quality enhancement, reduction of ammonia and greenhouse gases (GHGs) emissions, and water protection. While these actions in Poland are voluntary for farmers, their implementation can yield environmental, economic, and social benefits [Jayaraman et al. 2021, Petsakos et al. 2023]. Through the support of environmentally friendly practices, the European Union aims to foster sustainable agricultural development, achieve environmental protection, and meet climate change objectives [Cuadros-Casanova et al. 2023]. However, barriers to their effective implementation within the EU-27 often vary and the factors affecting its employment often remain obscured [Heyl et al. 2021, Runge et al. 2022, Van Hoof 2023].

Despite extensive research on specific sustainable agri-practices under carbon farming has been widely demonstrating significant benefits such as a mitigation of the soil organic matter (SOM) decomposition, an increase in soil organic carbon (SOC) stock [Han et al. 2018, Wang et al. 2020], reduced volatile carbon and nitrogen losses [Velthof et al. 2020 , Bumbiere et al. 2022], improved soil health [Khangura et al. 2023], and protection water resources [Poláková et al. 2023], there is a knowledge gap regarding potential barriers to their adoption from the farmers' perspective [Sharma et al. 2021]. As far as the authors are concerned, up to date there was a lack of socio-agricultural survey studies conducted in Poland. It is alarming specifically addressing the lower-than-expected implementation levels of carbon farming measures recommended as part of the recently announced subsidized Polish eco-scheme: Carbon Farming and Nutrient Management [Eco-Scheme: Carbon Farming and Nutrient Management].

Therefore, to address uncertainties regarding contributing factors and potential barriers in the farmers' perspective on carbon farming and low-emission practices, aligning with the Farm to Fork Strategy [Billen et al. 2024] and the European Green Deal [Faichuk et al. 2022, Sikora 2021] we conducted a comprehensive survey study with 122 Polish farmers. Specifically, this study investigated farmers' viewpoints and knowledge of organic matter management measures facilitated by soil incorporation of manures, slurry and crop residues, conservation tillage, diversified crop structure, and intercropping.

The primary research question addressed in this study was: How do farmers in Poland perceive the six potent low-emission sustainable farming practices endorsed by CAP and carbon farming-related strategies? By exploring this question, the study aimed to contribute valuable insights to inform Polish agricultural policies. The study addressed the following key issues:

– what is the level of farmers' willingness to implement the practices proposed under the surveyed carbon farming measures in Polish agriculture?

– what factors influence farmers' point of view on carbon farming and low-emission agricultural measures in their farming households?

– how does farmers' education align with their perception of practices endorsed by the surveyed pro-environmental and pro-climate practices?

– is there any deriving effect between farmers' age, education, farm size, farming system and implementation of diversified crop structure, conservation tillage, cover crops and intercropping, manure and slurry soil incorporation, and straw return?

– what are the potential barriers to the implementation of surveyed pro-environmental and pro-climate practices in Polish agriculture?

To address these questions comprehensively, a two-fold survey approach was employed, consisting of the standardized questionnaire [Cheung 2020] and individual in-depth interviews – IDI [Eppich and Gormley 2019] executed on a group of 122 Polish farmers encompassing a diverse range of age, agricultural education levels, farming systems, and land-use area.

MATERIALS AND METHODS

Data collection

122 Polish farmers were randomly chosen across Poland encompassing a sample size vast enough to maintain a confidence interval not lower than 95% for the Polish farmers' general population. All regions (voivodeships) were analyzed collectively to ensure a socio-demographic perspective as representative of the entire Polish population as possible. Therefore, no specific regionalization was implemented during the survey process. Additionally, no sociodemographic targeting or other specific criteria were applied in selecting respondents, in order to capture the wide variability within the representative sample group.

The combination of structured questionnaires and IDI were utilized in order to research the farmers' perspective in carbon farming and low-emission measures. A structured questionnaire was prepared to endorse both demographic and factual inquiries structured in the combination of close-ended, open-ended, and rating scale questions regarding the information as follows:

– farmer's age – close-ended question;

– farmer's education – close-ended question;

– farm size – close-ended question;

– farm type – close-ended question;

– farm production focus – open-ended;

– farmer’s viewpoint and the willingness to employ the diversified crop structure, conservation tillage, crops and intercropping, manure soil incorporation within 12 h after application, slurry application without surface spreading, and straw return – Likert scale questions;

– farmer’s subjective assessment of: soil C stock increase; soil N stock increase; water pollution mitigation; air pollution mitigation; bureaucracy, formalities, controls; financial subsidies importance in employing pro-environmental and pro-climate measures – 10 points rating scale questions.

Utilizing individual in-depth interviews, each respondent was additionally asked six separate questions regarding different pro-environmental and pro-climate measures promoted by the surveyed pro-environmental and pro-climate measures outlined as follows:

Will you utilize, or are you already utilizing:

– diversified crop structure,
– conservation tillage (including no-till cultivation),
– cover crops and intercropping,
– manure soil incorporation within 12 hours after application,
– slurry application using techniques other than surface spreading,
– straw return (soil incorporation),
– in alignment with carbon farming and low-emission agricultural practices?

Subsequently, depending on whether the farmers answered yes or no, they were asked to explain why or why not they are utilizing or would be willing or not willing to employ certain measures.

Data utilization and analysis

Standard grouping approaches were utilized to analyze the responses of surveyed farmers. General farming households were classified based on the Eurostat Farm Typology Glossary [EUROSTAT 2021]. Principal production type groups were established based on the main agricultural products. Groups of farmers’ age, farmer’s education and farm size were established based on the related answers. Each group had their shares calculated as a percentage of all respondents (n = 122).

To explore deriving factors between farmers’ age, education, farm size and the factors affecting their willingness to employ surveyed pro-environmental and pro-climate measures, Principal component analysis (PCA) [Abdi and Williams 2010] was performed using the R environment with FactomineR package [Lê et al. 2008].

To achieve variables comparability requitement [Abdi and Williams 2010], PCA was computed after standardizing the data with the formula:

$$x_{sc} = \frac{x_i - mean\ (x)}{sd(x)},$$

where x_{sc} is the scaled variable, x_i is the individual variable, *mean* (x) is the mean of x values, and $sd(x)$ is the standard deviation of x values. As for the descriptive responses, each answer got assigned an individual value based on the standard scaling system in e.g. education level from primary, secondary, and higher education got changed into values 1, 2, and 3 respectively, where the higher number corresponded to higher scale value. Likert answers were scaled in the same manner attributing more convincing answers to the higher numbers. Surveyed factors affecting farmers' willingness to employ certain measures were scaled in alignment to the 10-point rating scale in which respondents gave their answers.

RESULTS

Surveyed farming households' characteristic

The survey conducted with 122 Polish farmers revealed a substantial diversity in the farming systems employed in Poland (Tab. 1). Utilizing the classification proposed by the Eurostat Farm Typology Glossary, over 40% of the analyzed farming households can be classified as crop-specialist holdings, while livestock-specialist holdings and mixed-farming holdings each constituted approximately 30%. The majority of the surveyed specialist

Table 1. Distribution of surveyed farming holdings key characteristics (n = 122)

Characteristics	Category	Percentage (%)	n
General type[1]	livestock-specialist holding	27.84	34
	crop-specialist holding	42.62	52
	mixed-farming holding	29.51	36
Principal production type	pig	4.92	6
	dairy cattle	7.38	9
	beef cattle	9.02	11
	poultry	2.46	3
	sheep and goats	0.82	1
	horses	3.28	4
	horticulture	10.66	13
	cereals and oilseeds	16.39	20
	root crops	7.38	9
	orchards	8.20	10
	crops and livestock combined	29.51	36
Farm size	<10 ha	18.85	23
	10–25 ha	32.79	40
	26–50 ha	23.77	29
	51–100 ha	18.03	22
	>100 ha	6.56	8
Farmer's age	<20 y/o	9.02	11
	25–35 y/o	40.98	50
	36–50 y/o	32.79	40
	51/65 y/o	14.75	18
	>65 y/o	2.46	3
Farmer's education	primary education	46.72	57
	secondary education	27.05	33
	higher education	26.23	32

[1] Eurostat Farm Typology Glossary [EUROSTAT 2021]

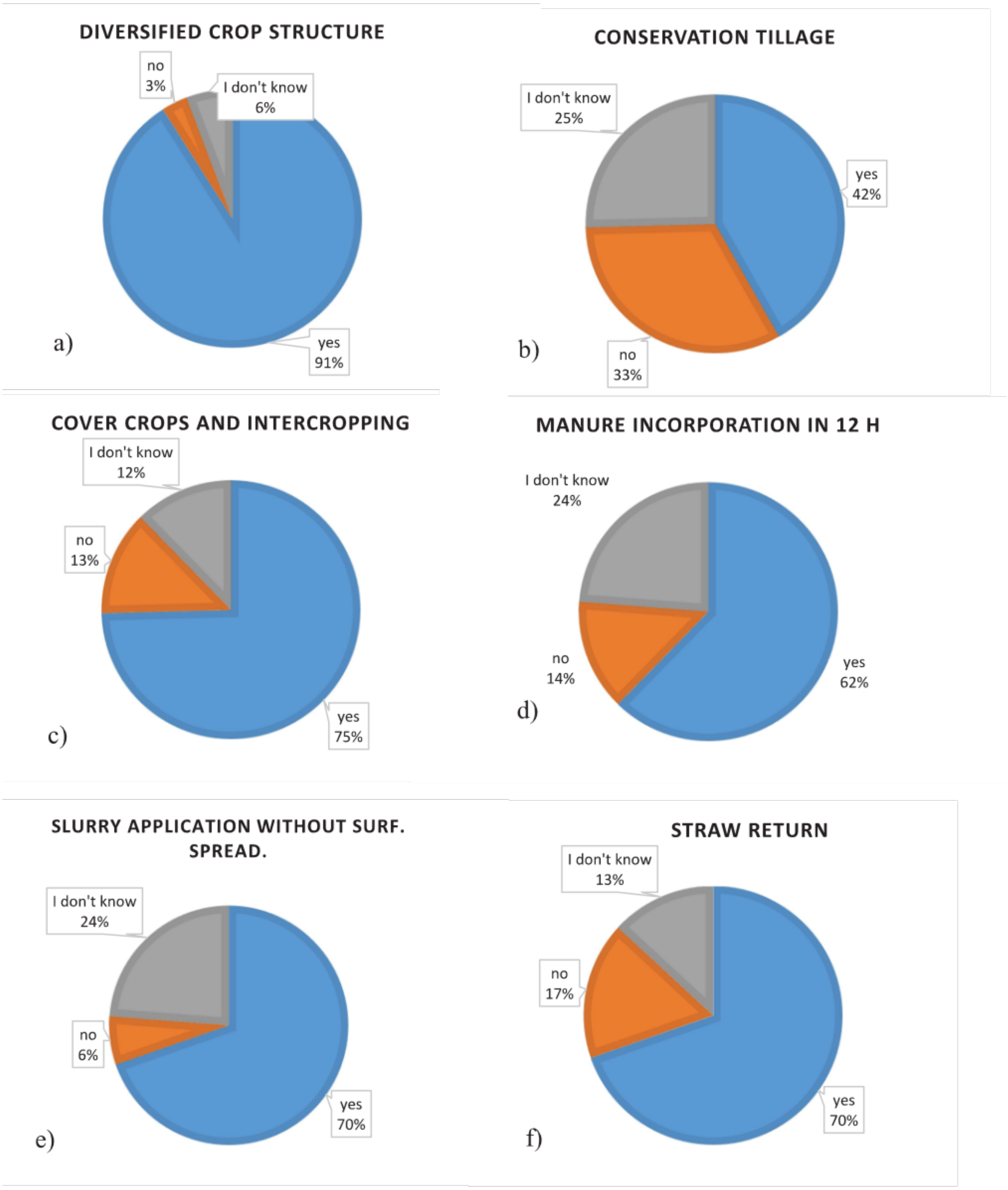

Fig. 1. Pie charts of the distribution of surveyed farmers' willingness to utilize: a) diversified crop structure; b) conservation tillage; c) cover crops and intercropping; d) manure soil incorporation within 12 h after application; e) slurry application employing techniques other than surface spreading; f) straw return

farming holdings indicated a focus on cereal and oilseed production (16.39% of respondents), with horticulture as the second most prevalent focus (10.66% of respondents). Regarding livestock specialist holdings, beef production was found to be the most prevalent (9.02% of respondents), followed by cattle dairy production (7.38% of respondents).

The farm size distribution within the tested group revealed that the majority of respondents engage in farming on land areas ranging from 10 to 25 ha (32.79% of respondents), making this the most prevalent category. The second most common farm size falls within the range of 26 ha to 50 ha, accounting for 23.77% of respondents. Farms smaller than 10 hectares constituted the third most prevalent group (18.85% of respondents), while those exceeding 100 hectares were the least common (6.56% of respondents).

The majority of respondents fell within the age range of 25–35 years old, constituting 40.98% of the total respondents. The second-largest age group comprised farmers between 36-50 years old, accounting for 32.79% of respondents, while the smallest group consisted of farmers over 65 years old, making up only 2.46%. Regarding education, nearly half of the surveyed farmers (46.72% of respondents) reported having obtained only primary education. Secondary education was attained by 27.05% of respondents, while 26.23% indicated having acquired higher education.

Farmers willingness to employ surveyed carbon farming and low-emission measures

Subsequent analysis of IDI responses revealed that the motivations behind farmers' interest in employing the surveyed carbon farming measures vary significantly. For diversified crop structure, over half of the respondents mentioned the potential to increase SOC content in the longer perspective as the main reason (50.82% of respondents). The second most common response emphasized the pivotal role of financial subsidies (22.95% of respondents). In contrast, less than 20% of respondents indicated biodiversity reasons as the primary motivation for utilizing this measure. Conversely, the barriers identified in the implementation of diversified crop measures include a uniform production profile and the land use area, which pose technical difficulties. Additionally, only less than 2% of the respondents mentioned that they do not perceive any benefits from employing these measures.

Conservation tillage emerged as the most contentious measure in the perception of surveyed farmers. The predominant arguments in favor of this measure included its positive impact on soil microbial activity (19.67% of respondents) and its effectiveness in mitigating SOM decomposition (14.75% of respondents). However, positive responses were less frequent than arguments against the measure, or the reasons why farmers might hesitate to adopt it. The most commonly mentioned argument against conservation tillage was farmers' attachment to traditional, standard cultivation practices involving regular tillage (24.59% of respondents). The second most frequently mentioned barrier was the lack of machinery for conservation tillage (21.31% of respondents), followed by the lack of perceived visible economic and environmental advantages (12.3% of respondents).

For the cover crops and intercropping measures, a substantial number of respondents highlighted the increase in SOC as the primary factor convincing them to adopt these measures (47.54% of respondents). However, respondents frequently mentioned drawbacks, with increased production costs being a common concern. Additionally, more than 25% of respondents collectively expressed reservations due to the perceived lack of economic and environmental benefits associated with these measures.

In the context of incorporating manures within 12 h from application, the aspects of reducing ammonia and GHG emissions played a pivotal role. Over 50% of respondents reported a cumulative acknowledgment of these benefits, with a stronger emphasis on soil sorption of ammoniacal nitrogen (38.52% of respondents). The primary argument against the adoption of this measure centered around farm-size issues and the inability to incorporate manure in a timely manner (18.85% of respondents). Approximately 7.4% of respondents mentioned that they do not apply manure or other natural fertilizers due to the absence of livestock production and the financial constraints prohibiting purchase.

In parallel with the timely incorporation of manure, the utilization of techniques other than surface spreading for slurry application is primarily justified by its positive impact on reducing ammonia losses. The key emphasis is on maximizing ammoniacal nitrogen sorption in the soil (38.52% of respondents) and mitigating gaseous losses (21.32% of respondents). The most frequently mentioned obstacle in implementing this measure is the absence of the requisite equipment for soil injection or other applicable techniques (13.11% of respondents).

Approximately 40% of respondents expressed their willingness to implement complete straw return as a means to enhance SOC stock, which was identified as the primary rationale for employing this measure. The second most prevalent convincing argument was the anticipated increase in soil microbial activity, as indicated by 23.77% of respondents. In contrast, 18.85% of surveyed farmers mentioned the inability to incorporate straw due to its necessity in livestock husbandry. Additionally, 4.92% of respondents pointed out that the utilization of straw in energy production hindered them from adopting straw return. Furthermore, 6.58% of respondents did not perceive any discernible economic or environmental benefits resulting from complete straw soil incorporation. Detailed IDI responses both in favor of and against specific measures are outlined in Table 2.

Deriving effects between the Polish farming households' characteristics and farmers' willingness to employ surveyed pro-environmental and pro-climate measures

Principal Component Analysis revealed substantial interrelations among farmer's age, education, farm size, and the factors influencing their willingness to adopt specific measures (Fig. 2). Farmer's education, coupled with the inclination to enhance soil N and C stocks, as well as to mitigate water and atmosphere pollution, were most prominently represented in PC1 (eigenvalue = 50.8%) and PC2 (eigenvalue = 28.9%). This underscores that these factors exerted the most substantial influence on the variability of farmers' responses.

The education level and farm size exhibited a strong positive correlation with farmers' willingness to employ conservation tillage and a diversified crop structure. Notably, both of these measures contradicted the farmer's age, which displayed a negative effect. Farmer's age demonstrated a positive correlation with their willingness to implement complete straw return. No discernible effects of farmer's age, education, or farm size were identified concerning the impacts of financial subsidies. However, bureaucracy, and to a lesser extent, atmosphere protection, tended to influence the decisions of older farmers more strongly than those of younger farmers.

Table 2. In-depth interview (IDI) answers obtained from surveyed farmers (n = 122)

Measure	IDI answers after categorization	Percentage (%)	n
Diversified crop structure	Yes, to increase biodiversity.	17.21	21
	Yes, to increase SOC stock in a longer perspective.	50.82	62
	Yes, mainly to receive additional subsidies.	22.95	28
	No, due to the uniform production profile.	3.28	4
	No, due to the size of the area and technical difficulties.	4.10	5
	No, due to the lack of visible economic and environmental benefits.	1.64	2
Conservation tillage	Yes, to reduce the decomposition of soil organic matter.	14.75	18
	Yes, to increase the soil microbiological activity.	19.67	24
	Yes, mainly to receive additional subsidies.	7.38	9
	No, due to the lack of appropriate machines for conservation tillage.	21.31	26
	No, due to being attached to the traditional form of soil cultivation.	24.59	30
	No, due to the lack of visible economic and environmental benefits.	12.30	15
Cover crops and inter-cropping	Yes, to reduce the risk of nitrates leaching into groundwater.	11.48	14
	Yes, to increase the soil carbon stock.	47.54	58
	Yes, mainly to receive additional subsidies.	15.57	19
	No, due to the increase in cultivation costs.	18.03	22
	No, due to the lack of visible economic and environmental benefits.	7.38	9
Manure soil incorporation within 12 h after application	Yes, to reduce ammonia and greenhouse gas emissions.	14.75	18
	Yes, to maximize the sorption of ammoniacal nitrogen in the soil.	38.52	47
	Yes, mainly to receive additional subsidies.	9.02	11
	No, due to the too-vast area and technical difficulties.	18.85	23
	No, due to the lack of visible economic and environmental benefits.	11.48	14
	No, due to the inability to produce/obtain manure.	7.38	9
Slurry application without surface spreading	Yes, to reduce ammonia and greenhouse gas emissions.	21.31	26
	Yes, to maximize the sorption of ammonium nitrogen in the soil.	36.07	44
	Yes, mainly to receive additional subsidies.	12.30	15
	No, due to the too-vast area and technical difficulties.	3.28	4
	No, due to the lack of appropriate machines.	13.11	16
	No, due to the lack of visible economic and environmental benefits.	6.56	8
	No, due to the inability to produce/obtain slurry.	7.38	9
Straw return	Yes, to increase the soil carbon stock.	39.34	48
	Yes, to increase the soil microbiological activity.	23.77	29
	Yes, mainly to receive additional subsidies.	6.56	8
	No, due to the need to use straw in litter farming.	18.85	23
	No, due to the use of crop residues for energy production purposes.	4.92	6
	No, due to the lack of visible economic and environmental benefits.	6.56	8

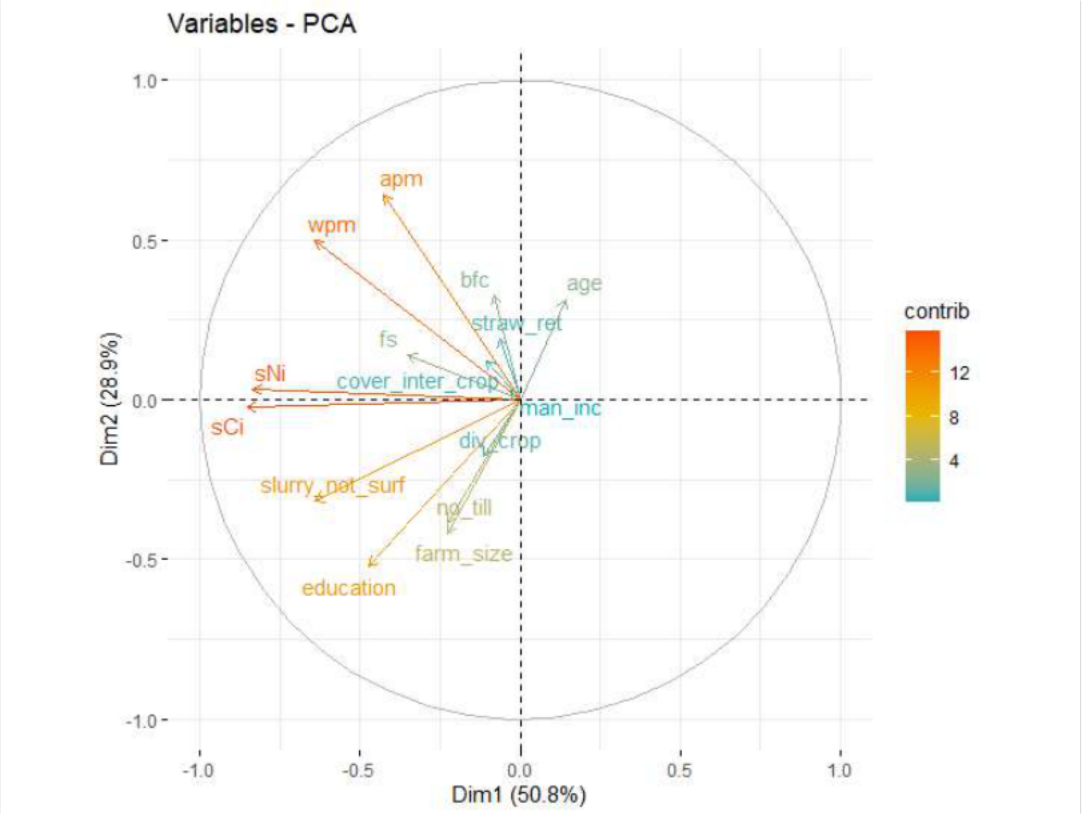

Fig. 2. Principal component analysis correlation circle. Each vector's length shows the quality of the variables on the factor map. The angle between the vectors indicates the correlation between the given variables: close to 0 degrees for strong positive correlation, close to 180 degrees for strong negative correlation, and close to 90 degrees for weak or near-zero correlation

Abbreviations: sCi – soil C stock increase; sNi – soil N stock increase; wpm – water pollution mitigation; apm – air pollution mitigation; bfc – bureaucracy, formalities, controls; fs – financial subsidies; div_crop – diversified crop structure; no_till – conservation tillage; cover_inter_crop - cover crops and intercropping; man_inc – manure soil incorporation within 12 h after application; slurry_not_surf – slurry application without surface spreading; straw_ret – straw return

The factor importance analysis revealed that aspects related to bureaucracy, formalities, and administrative controls played the least influential role in shaping farmers' willingness to implement the surveyed pro-environmental and pro-climate measures. Notably, the potential of certain measures to increase carbon and nitrogen stocks was identified as having the most substantial impact on farmers' perceptions. Although financial subsidies were indicated by a relatively low number of respondents as an essential factor (Tab. 2), they were found to have a considerable influence on farmers' willingness to utilize the measures as promoted with direct payments. This influence was stronger in decision-making than considerations related to water and air pollution mitigation, as depicted in Figure 3.

DISCUSSION

The results of the conducted survey indicate that the utilization of the analyzed carbon farming measures and low-emission is generally well-regarded in Poland. Of the six

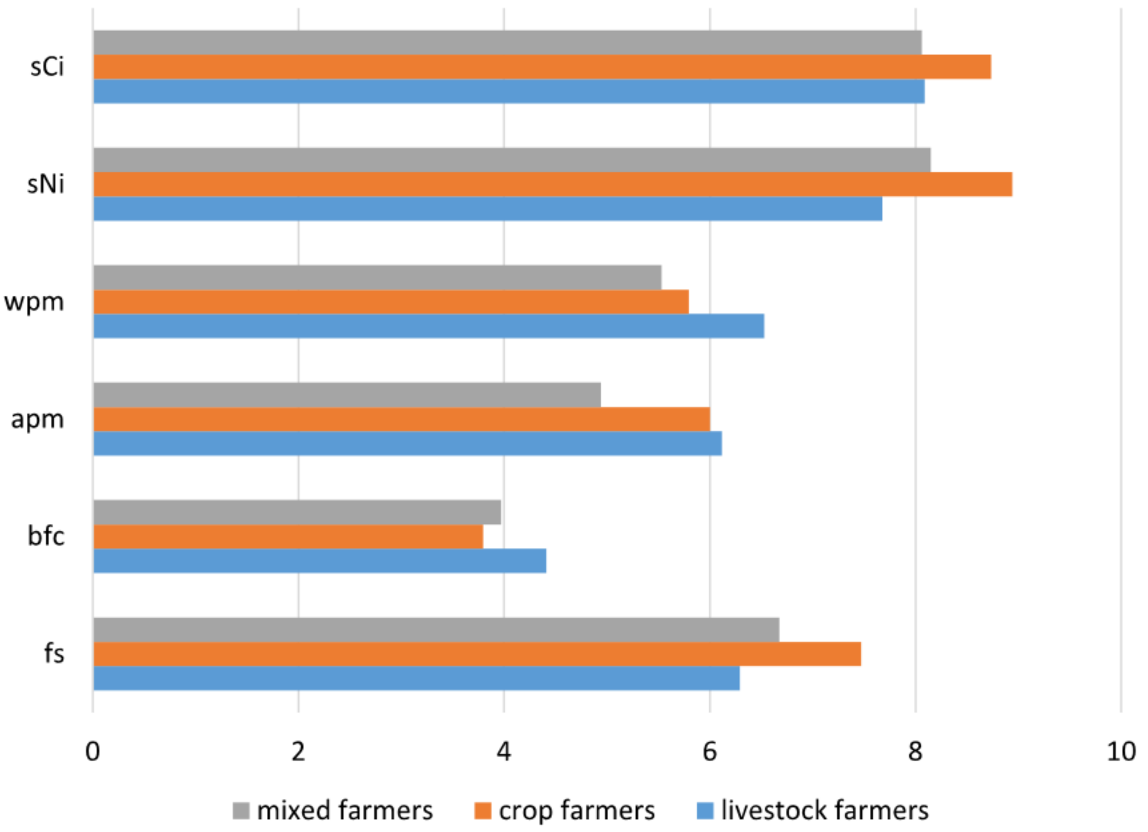

Fig. 3. Importance of the factors affecting the farmers' willingness to employ surveyed pro-environmental and pro-climate measures. The higher is depicted value the stronger the impact of the given factor

Abbreviations: sCi – soil C stock increase; sNi – soil N stock increase; wpm – water pollution mitigation; apm – air pollution mitigation; bfc – bureaucracy, formalities, controls; fs – financial subsidies

surveyed measures, five received positive assessments from over 60% of the respondents, demonstrating their willingness to adopt these measures (Fig. 1, Tab. 2). Notably, conservation tillage cultivation was negatively or hesitantly judged by over 50% of the respondents, suggesting that its implementation may be more challenging compared to the other measures. Interestingly, the analysis of IDI responses revealed that the primary reason for not adopting conservation tillage was the farmers' preference for traditional cultivation methods (Tab. 2). This preference persisted despite their awareness of the potential carbon offsets associated with conservation tillage [Manley et al. 2005]. Additionally, less than 35% of surveyed farmers expressed a willingness to adopt conservation tillage for reasons other than financial subsidies, suggesting a need for further efforts to shift Polish farmers' perceptions of this practice. A similar study conducted among farmers in Tennessee, United States [Lo et al. 2021] indicated a preference for adopting conservation tillage over planting cover crops, contrasting with the perceptions of Polish farmers (Fig. 1). This contrast may suggest that Eastern Europe, including Poland, is still lagging in the adoption of conservation farming practices [Kertész and Madarász 2014]. Notably, the positive correlation between the education level of Polish farmers and their willingness to adopt conservation tillage (Fig. 2) implies that additional education could enhance farmers' positive perceptions of this measure.

Cover crops and intercropping have been identified as the second most frequently chosen pro-environmental and pro-climate measures in Poland, following diversified crop structure (Fig. 1). Farmers expressing a willingness to adopt these two measures have highlighted carbon stock increase as the most significant reason influencing their decision-making (Tab. 2). This suggests that Polish farmers may possess knowledge of the well-documented interactive effects of cover crops, intercropping, and diversified crop structure on SOM turnover, as extensively researched [Pagano et al. 2017, Schaefer et al. 2020, Firth et al. 2022, Ilakiya et al. 2023]. Notably, the carbon stock aspects emerged as among the most influential factors shaping farmers' perspectives in general (Figs 2 and 3). This finding supports the idea that emphasizing carbon stock considerations in farmers' education, particularly in the context of conservation farming [Jayaraman et al. 2022] could further enhance the willingness of Polish farmers to adopt no-till or minimal tillage cultivation techniques.

Manure incorporation within 12 h of application and slurry application using techniques other than surface spreading are two carbon farming measures where Poland lags behind many EU countries [Emmerling et al. 2020]. For instance, all farmers in the Netherlands are obligated to adopt these measures according to national regulations [Leenstra et al. 2019]. The conducted survey has proven that Polish farmers are aware of their positive impact on ammoniacal nitrogen stabilization in the soil (Tab. 2) and having a considerable impact on reducing volatile nitrogen losses [Velthof et al. 2003, Velthof and Mosquera 2011, Hou et al. 2015]. Only approx. 11% of respondents indicated that they do not see any visible and economic and environmental benefits for manure immediate incorporation, and less than 7% expressed similar sentiments regarding slurry injection or other relevant techniques. This suggests a crucial need for educating farmers on the potential advantages of reducing ammonia losses. Additionally, approximately 13% of respondents pointed to barriers in implementation, mentioning the lack of specialized machinery for slurry injection. Almost 19% of respondents mentioned other technical difficulties associated, often, with the vast agricultural areas, particularly regarding timely soil incorporation of manure (Tab. 2).

Such barriers were found to be minor regarding the complete straw return where the main argument against its utilization was the necessity to use straw in livestock production or litter farming in general (Tab. 2) This practice can also be perceived as a means of returning straw, particularly if the natural fertilizers produced in this manner contribute to closing the loop in even more favorable way, as suggested by Liu et al. [2017]. Conversely, various studies have demonstrated the enhancing effect of raw straw return on soil parameters [Su et al. 2020, Chen et al. 2022], aligning with the key reasons why some of the Polish farmers have been choosing to adopt this pro-environmental and pro-climate measure. These reasons emphasize its positive impact on soil carbon stock and soil microbial activity, as outlined in Table 2. Interestingly, straw return was the only measure in which willingness to utilize was strongly positively correlated with farmer's age (Fig. 2), which may indicate the need to focus the efforts to encourage the younger generations to consider complete straw return.

The factor importance analysis (Fig. 3) revealed that the bureaucracy, formalities, and administrative controls aspects play the least important role in shaping farmers' willingness to employ the surveyed pro-environmental and pro-climate measures. This suggests that formalities regarding the eco-schemes and other policy controls are not a substantial barrier to the implementation of carbon farming in Poland. Specific challenges were identified for certain measures, aligning with the perspective of assessed Polish farmers and highlighting potential barriers in the further utilization of the surveyed measures. These findings resonate with the challenges discussed by Cuadros-Casanova et al. [2023] regarding the implementation of CAP reform, indicating that overcoming identified barriers may not only support the implementation of carbon farming in Poland but also contribute to achieving the goals of the European Green Deal in broader perspective [Sikora 2021, Cuadros-Casanova et al. 2023].

CONCLUSIONS

The conducted survey shed light on the interrelation among various factors influencing farmers' willingness to adopt pro-environmental and pro-climate measures within carbon farming and low-emission practices. The most influential factor in farmers' decision-making was the potential of certain measures to enhance soil carbon and nitrogen stocks, surpassing the impact of financial subsidies, bureaucratic aspects, and farm-specific characteristics, including the farmer's age and farm size. Several barriers were pinpointed, with technical difficulties and a lack of specialized machinery emerging as notable hindrances for practices related to manure and slurry soil incorporation in a way of the surveyed practices. The conservation tillage was deemed the least plausible to implement on a national scale. This reluctance was attributed not only to the need for specialized machinery but also to a preference for the standard conventional tillage practices in Poland. Addressing these challenges, particularly in the context of conservation tillage, requires targeted educational activities related to the provision of advisory services in agriculture in this area. Raising awareness about the impact of surveyed measures on soil carbon stocks has been identified as the most potent mean to overcome the barriers identified in the survey.

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Lublin, 26 kwietnia 2024 r.

dr hab. Monika Skowrońska, prof. uczelni
Katedra Chemii Rolnej i Środowiskowej
Uniwersytet Przyrodniczy w Lublinie
ul. Akademicka 15, 20-950 Lublin
monika.skowronska@up.lublin.pl, (81) 445 69 95

Rada Dyscypliny Rolnictwo i Ogrodnictwo
Uniwersytetu Przyrodniczegow Lublinie

Oświadczenie o współautorstwie

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- **Skowrońska M., Kuśmierz S., Walczak J. 2024. Selected carbon and nitrogen compounds in a maize agroecosystem under the use of nitrogen mineral fertilizer, farmyard manure, urease, and nitrification inhibitors. Agriculture 14, 274. https://doi.org/10.3390/agriculture14020274** mój wkład polegał na udziale w opracowaniu koncepcji badań, zaplanowaniu i przeprowadzeniu badań naukowych, analizie wyników, przygotowaniu i redagowaniu manuskryptu.

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Monika Skowrońska
....
Podpis

Lublin, 22 kwietnia 2024 r.

dr hab. Przemysław Tkaczyk, prof. uczelni
Katedra Chemii Rolnej i Środowiskowej
Uniwersytet Przyrodniczy w Lublinie
ul. Akademicka 15, 20-950 Lublin
przemyslaw.tkaczyk@up.lublin.pl, (81) 445 68 30

Rada Dyscypliny Rolnictwo i Ogrodnictwo
Uniwersytetu Przyrodniczegow Lublinie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy: **Kuśmierz S., Skowrońska M., Tkaczyk P., Lipiński W., Mielniczuk J. 2023. Soil organic carbon and mineral nitrogen contents in soils as affected by their pH, texture and fertilization. Agronomy, 13, 267. https://doi.org/10.3390/agronomy13010267** mój udział polegał na analizie wyników badań.

Tkaczyk Przemysław
……………………………
podpis

Warszawa, 22 kwietnia 2024 r.

prof. dr hab. Wojciech Lipiński
Krajowa Stacja Chemiczno - Rolnicza w Warszawie
ul. St. Żółkiewskiego 17, 05-075 Warszawa
wlipinski@schr.gov.pl, (22) 290 42 05

Rada Dyscypliny Rolnictwo i Ogrodnictwo
Uniwersytetu Przyrodniczegow Lublinie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy: **Kuśmierz S., Skowrońska M., Tkaczyk P., Lipiński W., Mielniczuk J. 2023. Soil organic carbon and mineral nitrogen contents in soils as affected by their pH, texture and fertilization. Agronomy, 13, 267. https://doi.org/10.3390/agronomy13010267** mój udział polegał na analizie wyników badań.

……………………………
Podpis

Lublin, 22 kwietnia 2024 r.

dr Jacek Mielniczuk
Katedra Zastosowań Matematyki i Informatyki
Uniwersytet Przyrodniczy w Lublinie
ul. Głęboka 28, 20-612 Lublin
jacek.mielniczuk@up.lublin.pl, (81) 531 96 26

Rada Dyscypliny Rolnictwo i Ogrodnictwo
Uniwersytetu Przyrodniczegow Lublinie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy: **Kuśmierz S., Skowrońska M., Tkaczyk P., Lipiński W., Mielniczuk J. 2023. Soil organic carbon and mineral nitrogen contents in soils as affected by their pH, texture and fertilization. Agronomy, 13, 267. https://doi.org/10.3390/agronomy13010267** mój udział polegał na analizie statystycznej wyników badań.

....
Podpis

Kraków, 24 kwietnia 2024 r.

dr hab. Jacek Walczak
Instytut Ochrony Środowiska - Państwowy Instytut
Badawczy, Krajowy Ośrodek Bilansowania
i Zarządzania Emisjami (KOBiZE)
ul. Słowicza 32, 02-170 Warszawa
jacek.walczak@kobize.pl, (22) 569 6511

Rada Dyscypliny Rolnictwo i Ogrodnictwo
Uniwersytetu Przyrodniczegow Lublinie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy: **Skowrońska M., Kuśmierz S., Walczak J. 2024. Selected carbon and nitrogen compounds in a maize agroecosystem under the use of nitrogen mineral fertilizer, farmyard manure, urease, and nitrification inhibitors. Agriculture 14, 274. https://doi.org/10.3390/agriculture14020274** mój udział polegał na analizie wyników badań.

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