Szkoła Główna Gospodarstwa Wiejskiego
w Warszawie
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Modelowanie emisji metanu ze źródeł rolniczych z wykorzystaniem zdjęć satelitarnych o średniej rozdzielczości w różnej skali przestrzennej

Modeling methane emissions from agricultural sources using medium resolution satellite imagery at various spatial scales

Rozprawa doktorska

Doctoral thesis

Rozprawa doktorska wykonana pod kierunkiem:
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za nieocenioną pomoc, wsparcie oraz cenne wskazówki naukowe
podczas całego procesu pisania pracy.

Dziękuję również wszystkim pracownikom Katedry Biometrii SGGW,
a w szczególności Panu dr hab. Dariuszowi Gozdowskiemu,
Profesorowi Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie,
za merytoryczne wsparcie, cenne uwagi i życzliwość.

Szczególne podziękowania kieruję do mojej rodziny i przyjaciół,
za zrozumienie, nieustanne wsparcie i wiarę w moje możliwości.

Spis treści

Streszczenie

Metan (CH_4) jest jednym z głównych gazów cieplarnianych (GHG) przyczyniających się do globalnego ocieplenia i zmian klimatu. Chociaż występuje w atmosferze w mniejszych ilościach niż dwutlenek węgla, jego potencjał tworzenia efektu cieplarnianego jest co najmniej 27 razy większy w perspektywie 100 lat. Rolnictwo jest odpowiedzialne za znaczną część emisji CH_4 ze źródeł antropogenicznych – w zależności od kraju nawet w 43%. Głównym źródłem emisji jest hodowla zwierząt (fermentacja jelitowa, gospodarowanie odchodami zwierząt) oraz uprawa pól ryżowych.

W związku ze stale obserwowanym wzrostem emisji CH_4 do atmosfery niezwykle istotne są bardziej szczegółowe pomiary i analizy emisji GHG. Emisje CH_4 zmieniają się w czasie pod wpływem wielu zmiennych, takich jak liczba zwierząt gospodarskich, sposoby chowu, poziom rozwoju krajów (np. wskaźnik PKB, liczba ludności, użytkowanie gruntów), wydajność produkcji rolniczej i spożycie produktów zwierzęcych. Udowodnienie zależności i trendów pomiędzy powyższymi zmiennymi umożliwia lepsze zrozumienie problemu wzrostu emisji CH_4 do atmosfery. Analiza obserwacji satelitarnych i generowanie map emisji pozwala na bardziej precyzyjne oszacowanie źródeł i poziomów stężenia CH_4 w atmosferze. Dlatego podjęte badania miały na celu:

i. analizę przestrzennych, czasowych i sezonowych zmian zawartości CH_4 w atmosferze dla wybranych regionów o wysokiej koncentracji upraw ryżu, korzystając z danych z misji Sentinel-5P,
ii. analizę przestrzennego rozkładu emisji CH_4 z hodowli zwierząt gospodarskich na świecie i w Polsce.

Pierwsze dwie prace (I, II) dowiodły długoterminowego wzrostu i sezonowej zmienności poziomów stężenia CH_4 w atmosferze w regionach o wysokiej uprawie ryżu, na podstawie istotnych danych z komputerowego modelowania emisji CH_4 oraz obserwacji satelitarnych z instrumentu TROPOMI na pokładzie Sentinel-5P. Sezonowo, niższe emisje CH_4 odnotowano na początku roku, natomiast wyższe późnym latem, a więc podczas intensywnego wzrostu ryżu. Pomiar emisji CH_4 z uprawy ryżu jest łatwiejszy do wykonania w porównaniu do pomiaru emisji CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt z kilku kluczowych powodów. Pola upraw ryżu są często skoncentrowane na określonych, dużych obszarach o jednolitych warunkach, co

ułatwia monitorowanie emisji CH_4. Natomiast emisje pochodzące z fermentacji jelitowej i odchodów zwierzęcych są rozproszone na dużych obszarach, ponieważ pochodzą od wielu zwierząt rozmieszczonych na różnych pastwiskach i farmach. Emisje CH_4 od pojedynczego zwierzęcia są stosunkowo niskie w porównaniu do emisji z przemysłowych źródeł, takich jak wycieki gazu ziemnego. Dlatego w pracach III i IV skupiono się na modelowaniu matematycznym i analizie emisji CH_4 z hodowli zwierząt gospodarskich na poziomie globalnym oraz na poziomie lokalnym, dla gmin Polski.

Słowa kluczowe: metan, modelowanie emisji, zmiany klimatu, zmiany długoterminowe, zmienność sezonowa, Sentinel-5P

Abstract

Methane (CH_4) is one of the major greenhouse gases (GHG) contributing to global warming and climate change. Although it exists in the atmosphere in smaller quantities than carbon dioxide, its potential for creating a greenhouse effect is at least 27 times greater. Agriculture is responsible for a significant portion of CH_4 emissions from anthropogenic sources – up to 43% in some countries. The main sources of emissions are livestock farming (enteric fermentation, manure management) and rice paddy cultivation.

Due to the continuously observed increase in CH_4 emissions to the atmosphere, more detailed measurements and analyses of GHG emissions are extremely important. CH_4 emissions vary over time due to many variables such as the number of livestock, farming methods, the level of development of countries (e.g., GDP, population, land use), agricultural production efficiency, and consumption of animal products. Demonstrating the relationships and trends between these variables enables a better understanding of the issue of rising CH_4 emissions into the atmosphere. Analysis of satellite observations and the generation of emission maps allows for a more precise estimation of the sources and magnitudes of CH_4 emissions. Therefore, the undertaken studies aimed to:

i. analyze the spatial, temporal, and seasonal changes in CH_4 content in the atmosphere for selected regions with high rice cultivation concentration, using data from the Sentinel-5P mission.
ii. analyze the spatial distribution of CH_4 emissions from livestock farming worldwide and in Poland.

The first two studies (I, II) demonstrated the long-term increase and seasonal variability of CH_4 content in the atmosphere in regions with high rice cultivation, based on CH_4 emission modeling using satellite data from the TROPOMI sensor on board Sentinel-5P. Seasonally, lower CH_4 emissions were recorded at the beginning of the year, while higher emissions were noted in late summer, during the intensive growth of rice. Measuring CH_4 emissions from rice cultivation is more feasible compared to CH_4 emissions from enteric fermentation and manure management of livestock for several key reasons. Rice paddies are usually concentrated in specific areas, called rice fields. These fields are often relatively large and have uniform conditions, making CH_4 monitoring easier. In contrast, emissions from enteric fermentation are dispersed over large areas, as they originate from many animals distributed across various pastures and farms. CH_4

emissions from a single animal are relatively low compared to industrial sources, such as natural gas leaks. Therefore, studies III and IV focused on mathematical modeling and analysis of CH_4 emissions from livestock farming at the global level and locally for municipalities in Poland.

Keywords: methane, emission modeling, climate change, long-term changes, seasonal variability, Sentinel-5P

1. Wykaz publikacji będących podstawą rozprawy doktorskiej

Przygotowana rozprawa doktorska ma formę zbioru czterech opublikowanych i powiązanych tematycznie artykułów naukowych. Poniższe publikacje stanowią podstawę rozprawy i prezentują dane oryginalne:

I. **Kozicka K.**, Gozdowski D., Wójcik-Gront E. 2021. Spatial-temporal changes of methane content in the atmosphere for selected countries and regions with high methane emission from rice cultivation. *Atmosphere* 12(11):1382. DOI: 10.3390/atmos12111382.
Impact Factor – 3,1; MNiSW – 70

II. **Kozicka, K.**, Orazalina, Z., Gozdowski, D., Wójcik-Gront, E. 2023. Evaluation of temporal changes in methane content in the atmosphere for areas with a very high rice concentration based on Sentinel-5P data. *Remote Sensing Applications: Society and Environment,* 30, 100972. DOI: 10.1016/j.rsase.2023.100972.
Impact Factor – 4,7; MNiSW – 100

III. **Kozicka, K.**, Žukovskis, J., Wójcik-Gront, E. 2023. Explaining global trends in cattle population changes between 1961 and 2020 directly affecting methane emissions. *Sustainability* 15(13):10533. DOI: 10.3390/su151310533.
Impact Factor – 3,9; MNiSW – 100

IV. **Kozicka, K.**, Ollik, M., Wójcik-Gront, E. 2024. Spatial distribution of CH_4 emissions from livestock farming in Poland: A comparison of 2010 and 2020. *Geografisk Tidsskrift-Danish Journal of Geography*, 1–12. DOI: 10.1080/00167223.2024.2350040.
Impact Factor – 2,3; MNiSW – 40

Suma Impact Factor – 14
Suma MNiSW – 310

Punktacja została podana na podstawie Journal Citation Reports (Clarivate Analytics, 2022 i 2023) oraz wykazów czasopism naukowych i recenzowanych materiałów z konferencji międzynarodowych (Komunikaty Ministra Nauki z dnia 1 grudnia 2021 r., 17 lipca 2023 r., 05 stycznia 2024 r.).

2. Wstęp i uzasadnienie podjęcia tematu

Metan (CH_4), obok dwutlenku węgla (CO_2) i podtlenku azotu (N_2O), jest jednym z głównych gazów cieplarnianych (GHG, ang. *greenhouse gases*) przyczyniających się do globalnego ocieplenia i zmian klimatu. Emitowany do atmosfery utrzymuje się średnio przez około dekadę, a więc znacznie krócej niż CO_2. Z drugiej jednak strony pochłania więcej energii cieplnej emitowanej z powierzchni Ziemi. Efekt netto krótszego czasu życia i wyższej absorpcji energii znajduje odzwierciedlenie w potencjale tworzenia efektu cieplarnianego (GWP, ang. *global warming potential*). Szacuje się, że GWP CH_4 jest 27-30 razy większy niż CO_2 w perspektywie 100 lat (He i in., 2020; Tsuruta i in., 2017).

Źródła emisji CH_4 dzieli się na naturalne (tereny podmokłe, jeziora, pożary) oraz źródła antropogeniczne, do których zaliczany jest przemysł związany z wydobyciem, dystrybucją i konsumpcją paliw kopalnych (węgiel, ropa i gaz), a także sektor gospodarki odpadami. Antropogenicznym źródłem emisji jest także sektor rolniczy, który odpowiada za ponad jedną czwartą całkowitych emisji CH_4 na świecie. Największym źródłem emisji CH_4 jest hodowla zwierząt gospodarskich, gdzie CH_4 jest wytwarzany podczas fermentacji jelitowej głównie u przeżuwaczy oraz, w mniejszym stopniu, u zwierząt monogastrycznych (de Gouw i in., 2020; Karakurt i in., 2012; Yusuf i in., 2012). CH_4 produkowany jest w żwaczu w wyniku trawienia i fermentacji paszy przez mikroorganizmy metanogeniczne. Szacuje się, że około 95% tego gazu jest emitowane poprzez odbijanie, podczas gdy pozostałe 5% uwalniane jest przez odbytnicę (Ramin i in., 2020). Emisje z fermentacji jelitowej zależą od rodzaju, jakości i strawności paszy. Dodatkowo, ilość spożywanej paszy ma istotny wpływ na produkcję CH_4 – większe spożycie paszy przekłada się na wyższe emisje tego gazu. Spożycie paszy zależy od wielkości zwierzęcia, tempa wzrostu oraz produkcyjności, np. produkcji mleka lub ciąży (Johnson & Johnson, 1995; Ulyatt & Lassey, 2001). Oprócz fermentacji jelitowej do emisji CH_4 z hodowli zwierząt przyczynia się również gospodarowanie odchodami zwierząt gospodarskich. Istotnym czynnikiem jest ilość wyprodukowanych odchodów, na którą wpływa liczba zwierząt. Ważny jest również system przechowywania odchodów, ponieważ CH_4 powstaje w warunkach beztlenowych, np. podczas przechowywania płynnych odchodów zwierząt. Dłuższy czas składowania odchodów może przyczyniać się do zwiększenia tempa emisji CH_4 (Dalby i in., 2021; Philippe i in., 2007; Steed & Hashimoto, 1994). Systemy utrzymania zwierząt na ściółce oraz składowanie odchodów na pastwiskach lub polach uprawnych, sprzyjają mniejszej emisji CH_4, ponieważ odbywa się to w warunkach tlenowych (Montes i in., 2013).

Uprawa ryżu stanowi kolejne źródło emisji CH_4 z rolnictwa, odpowiadając za około 8% całkowitej antropogenicznej emisji CH_4 (Global Methane Initiative, 2020). Emisje te są istotne ze względu na rosnące potrzeby żywnościowe na świecie, które mogą być zaspokojone poprzez zwiększenie produkcji ryżu, zwłaszcza w krajach Azji Południowo-Wschodniej (Prasad i in., 2017). CH_4 powstaje w wyniku zalewania pól, a więc w warunkach beztlenowych idealnych do życia dla mikroorganizmów metanogenicznych, których produktem oddychania jest CH_4 (Ji i in., 2018; Sanchis i in., 2012). Materia organiczna, głównie słoma ryżowa, ulega rozkładowi podczas okresu deszczowego i powodzi, podobnie jak nowo wytworzone części roślin. CH_4 jest uwalniany do atmosfery głównie poprzez aerenchymę roślin, a także poprzez dyfuzję rozpuszczonego CH_4 przez warstwę wody i pęcherzyki powietrza tworzone na przykład przez faunę glebową i uwalniane podczas mechanicznej uprawy gleby (Le Mer & Roger, 2001; Neue i in., 1990; Nouchi i in., 1994).

W związku ze stale obserwowanym wzrostem emisji CH_4 do atmosfery niezwykle istotne są bardziej szczegółowe pomiary i analizy emisji GHG, mające na celu dokładniejsze określenie źródeł i skali emisji. Metody „bottom-up" polegają na zbieraniu danych z poszczególnych procesów przemysłowych lub sektorów, takich jak sektor energetyczny czy rolnictwo, aby oszacować całkowite emisje na poziomie regionalnym lub krajowym. Wytyczne Międzyrządowego Zespołu ds. Zmian Klimatu (IPCC) są powszechnie stosowane do szacowania lokalnych emisji GHG. Emisje te są później raportowane do baz danych Ramowej Konwencji Narodów Zjednoczonych w sprawie Zmian Klimatu (UNFCCC). Do oszacowania emisji CH_4 z hodowli zwierząt gospodarskich wymagana jest definicja kategorii zwierząt gospodarskich, roczna populacja oraz, w bardziej złożonych metodach, szczegółowe dane dotyczące spożycia energii brutto i współczynnika emisji CH_4 dla każdej kategorii zwierząt (Eggleston i in., 2006).

Monitorowanie poziomów stężenia GHG w atmosferze jest również możliwe dzięki obserwacjom z użyciem satelitów. W porównaniu do metod „bottom-up", takie narzędzia dostarczają ogólny obraz emisji nie tylko na poziomie lokalnym, ale również globalnym. W badaniu przeprowadzonym przez Maasakkers i in., (2021) wykorzystano satelitę GOSAT, z którego uzyskano pomiary emisji CH_4 w latach 2010-2015 dla całego świata, a następnie porównano je z raportami emisji z Environmental Protection Agency (EPA) Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). Średnie szacunki emisji CH_4 uzyskane za pomocą satelity GOSAT różniły się od tych w raportach. Rozbieżność dotyczyła głównie sektorów produkcji ropy naftowej i gazu ziemnego, w których stwierdzono wyższe emisje niż w GHGI EPA, odpowiednio o 35% i 22%. Zaobserwowano również tendencję wzrostową emisji antropogenicznych w USA w latach 2010-2015 o 0,4%, w przeciwieństwie do spadku zgłoszonego przez EPA GHGI. Ponadto emisje pochodzące z wydobycia ropy naftowej i gazu ziemnego w Meksyku były wyższe niż w wykazie krajowym.

Najnowsze pomiary emisji GHG dostarcza obecnie satelita Europejskiej Agencji Kosmicznej (ESA) Copernicus z Misji Sentinel-5 Precursor (Sentinel-5P). Znajdujący się na jego pokładzie instrument TROPOMI (TROPOspheric Monitoring Instrument) charakteryzuje się wysoką rozdzielczością przestrzenną (7 × 7 km) i krótkim czasem rewizyty. Dzięki temu możliwe jest dokładne zbadanie jakości powietrza w oparciu o pomiary GHG, w tym CH_4 (Hasekamp i in., 2021). Według badań Hu i in. (2018) oraz Sha i in. (2021) dane z Sentinel-5P można uznać za wiarygodne do oceny poziomów stężenia CH_4 na całym świecie. Obserwacje satelitarne zostały porównane z pomiarami naziemnymi z Total Carbon Column Observing Network (TCCON) i danymi pochodzącymi z obserwacji satelitarnych GOSAT. W większości przypadków odchylenie standardowe różnicy pomiaru poziomów stężenia CH_4 przez Sentinel-5P oraz TCCON nie przekraczało 15 ppb (ang. *parts per bilion*). Średnia różnica pomiędzy poziomami stężenia CH_4 w atmosferze uzyskana z pomiarów Sentinel-5P i GOSAT wyniosła 13,6 ppb, odchylenie standardowe – 19,6 ppb, a współczynnik korelacji Pearsona – 0,95. Względna różnica pomiarów poziomów stężenia CH_4 pomiędzy Sentinel-5P a TCCON jest mniejsza niż 1%, a bardzo wysoki współczynnik korelacji potwierdza zgodność między tymi pomiarami.

Większość badań dostępnych w literaturze dotyczy modelowania emisji CH_4 z sektorów energetycznych i przemysłowych lub ogranicza się do analizy emisji tylko na poziomie krajowym lub w krótkim przedziale czasowym. Przykładem jest praca Dangala i in. (2017), w której zaobserwowano rosnący trend emisji CH_4 z hodowli zwierząt w latach 1890-2014. Analizę przeprowadzono jednak tylko dla Stanów Zjednoczonych, Australii, Brazylii, Kanady, Chin i Mongolii. W zależności od poziomu rozwoju gospodarczego danego kraju, produkcja bydła wykazuje zróżnicowany stopień intensywności, co przekłada się na emisje CH_4 (Chang i in., 2021). Wydajność produkcji mleka i wołowiny w krajach słabiej rozwiniętych charakteryzuje się niską efektywnością, co skutkuje wyższą emisją CH_4 na jednostkę produktu w porównaniu z krajami bardziej rozwiniętymi. Na przykład, roczna wydajność mleczna na krowę w USA jest około 6 razy wyższa niż w Indiach czy Pakistanie. Natomiast, produkcja GHG, wyrażona w kg ekwiwalentu CO_2 kg^{-1} mleka, wynosi od 1,3 dla krajów rozwiniętych, takich jak USA, do 7,4 dla krajów Afryki Środkowej. Z drugiej jednak strony, emisje CH_4 na jedną sztukę bydła mogą być niższe w krajach słabiej rozwiniętych ze względu na mniej intensywną produkcję oraz niższy poziom żywienia zwierząt (Britt i in., 2018). Wzrastająca populacja na całym świecie wymaga zwiększenia produkcji żywności, w tym mleka i wołowiny, co można osiągnąć poprzez poprawę wydajności produkcji zwierzęcej. Z praktycznego punktu widzenia zrównoważona produkcja bydła powinna być opłacalna ekonomicznie, zapewniając jednocześnie wysoką wydajność i niskie emisje na jednostkę produkcji (Prathap i in., 2021; Salter, 2017). Analiza zmian w populacjach zwierząt hodowlanych oraz emisji GHG na poziomie krajowym i światowym jest kluczowa dla działań mających na celu łagodzenie zmian klimatu.

Niniejsze badania, będące częścią rozprawy doktorskiej, dostarczają kompleksowej analizy emisji CH_4 z rolnictwa, co ma istotne znaczenie dla zrozumienia i łagodzenia globalnych zmian klimatycznych. W celu dokładnej oceny długoterminowych i sezonowych zmian poziomów stężenia CH_4 w atmosferze, szczególnie w kontekście emisji związanych z uprawą ryżu w Azji Południowo-Wschodniej, wykorzystano zaawansowane technologie, takie jak dane z satelity Sentinel-5P. Publikacje I i II są jednymi z pierwszych prac na świecie wykorzystujących dane TROPOMI do analizy poziomów stężenia CH_4 w atmosferze. Monitorowanie GHG za pomocą satelitów stanowi zaawansowaną metodę analizy poziomów stężenia gazów w atmosferze, w tym CH_4, na poziomie globalnym. Obserwacje umożliwiają analizę przestrzennych i czasowych trendów w emisji CH_4, identyfikację obszarów o podwyższonym poziomie emisji oraz ocenę wpływu różnych sektorów gospodarki na ogólne poziomy stężenia CH_4 w atmosferze. W kontekście monitorowania emisji CH_4 z uprawy ryżu, obserwacje satelitarne są bardzo efektywne. Pola ryżowe są skoncentrowane w określonych regionach, co ułatwia wykrywanie i pomiar emisji CH_4 przez satelity. Jednolite warunki na polach ryżowych zapewniają stabilne środowisko do produkcji CH_4, co umożliwia monitorowanie emisji przez dłuższy okres. Instrument

TROPOMI na pokładzie satelity Sentinel-5P jest w stanie wykrywać zmiany poziomów stężenia CH_4 nad dużymi obszarami rolniczymi, co pozwala na identyfikację trendów emisji CH_4 podczas różnych etapów wzrostu ryżu. Uzyskane dane przestrzenne i czasowe pomagają zrozumieć sezonowe wzorce i długoterminowe trendy emisji CH_4 z pól ryżowych. Z kolei monitorowanie emisji CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt stanowi większe wyzwanie. Emisje te są wysoce rozproszone, ponieważ pochodzą od licznych zwierząt rozmieszczonych na różnych pastwiskach i farmach. To rozproszenie utrudnia satelitom dokładne określenie konkretnych źródeł CH_4. Ponadto emisje CH_4 od pojedynczych zwierząt są stosunkowo niskie, co komplikuje wykrycie znaczących koncentracji emisji w określonym obszarze. Pomimo że satelity mierzą ogólne poziomy stężenia CH_4 w atmosferze, identyfikacja i przypisanie tych emisji do fermentacji jelitowej wymaga dodatkowych pomiarów naziemnych oraz modelowania w celu zwiększenia precyzji. Tylko w ten sposób można uzyskać pełny obraz przestrzenny i czasowy emisji CH_4, co pozwala na bardziej precyzyjne oszacowanie źródeł i wielkości emisji oraz ocenę wpływu różnych praktyk rolniczych i gospodarczych na te emisje.

Dlatego przeprowadzono wielowymiarową analizę emisji CH_4 na świecie, opartą na trendach dotyczących pogłowia bydła oraz innych zmiennych opisujących poszczególne kraje. Wyniki tych badań pozwoliły na lepsze zrozumienie dynamiki emisji CH_4 z sektora rolniczego, co ma istotne znaczenie dla opracowywania skutecznych strategii redukcji emisji GHG w tym sektorze. Wielowymiarowa analiza danych to narzędzie badawcze, które umożliwia analizę różnych aspektów związanych z emisją CH_4 na poziomie krajowym. Możliwe jest również zbadanie wielu zmiennych opisujących różne kraje i regiony, takie jak struktura gospodarcza, liczba ludności, poziom rozwoju ekonomicznego czy praktyki rolnicze, oraz jak te czynniki wpływają na emisję CH_4. Wielowymiarowe analizy danych pozwalają na identyfikację relacji i wzorców, które mogą nie być widoczne przy użyciu tradycyjnych metod analitycznych. Na przykład, badania mogą wykazać, że rozwijające się kraje o dużej liczbie ludności i rozwiniętym sektorze rolnym mają tendencję do wyższych emisji CH_4, podczas gdy kraje rozwinięte z zaawansowanymi technologiami w hodowli bydła mogą charakteryzować się niższymi emisjami na jednostkę produkcji. Wielowymiarowe analizy danych mogą również pomóc w identyfikacji grup krajów o podobnych wzorcach emisji CH_4. Dzięki temu można opracować bardziej efektywne strategie redukcji emisji, dostosowane do specyficznych potrzeb i warunków poszczególnych regionów. Na przykład, kraje o intensywnym rolnictwie mogą skupić się na optymalizacji praktyk hodowlanych, podczas gdy kraje z dużymi obszarami bagien mogą skoncentrować się na ochronie i zarządzaniu terenami podmokłymi.

W kolejnych badaniach wykorzystano dane z Powszechnego Spisu Rolnego prowadzonego w Polsce z roku 2010 i 2020 w celu analizy emisji CH_4 pochodzących od zwierząt gospodarskich. Szacowanie emisji CH_4 na poziomie gminnym dostarcza bardzo szczegółowego obrazu przestrzennego w porównaniu do tradycyjnych krajowych lub regionalnych ocen. Analiza danych z dwóch różnych okresów (2010 i 2020) pozwala na zidentyfikowanie trendów i ewentualnych zmian w emisjach CH_4 na przestrzeni lat, co jest kluczowe dla podejmowania skutecznych działań naprawczych i formułowania nowych polityk dotyczących ograniczania emisji GHG.

Tego rodzaju analizy są szczególnie istotne w kontekście globalnej walki ze zmianami klimatu. Poprzez zrozumienie, jak różne czynniki wpływają na emisję CH_4, naukowcy i decydenci mogą lepiej planować i wdrażać działania mające na celu ograniczenie emisji GHG na całym świecie.

3. Cel, zakres pracy i hipotezy badawcze

Oryginalne rozwiązanie problemu naukowego w przedstawionych badaniach polega na zastosowaniu nowoczesnych, zaawansowanych technologii satelitarnych do monitorowania poziomów stężenia CH_4 w atmosferze, szczególnie z upraw ryżu. W pracy zastosowano podejście polegające na integracji danych satelitarnych z modelowaniem matematycznym, co umożliwia bardziej precyzyjne szacowanie i rozróżnienie źródeł emisji CH_4.

3.1. Wykorzystanie danych satelitarnych Sentinel-5P ze spektrometru TROPOMI do analizy długoterminowych i sezonowych zmian poziomów stężenia CH_4 w atmosferze w regionach o wysokiej koncentracji upraw ryżu

Celem badawczym była analiza przestrzennych, czasowych oraz sezonowych zmian poziomów stężenia CH_4 w atmosferze nad regionami o wysokiej koncentracji upraw ryżu. Hipoteza badawcza zakładała, że dane satelitarne Sentinel-5P ze spektrometru TROPOMI są w stanie wykrywać zmiany poziomów stężenia CH_4 w regionach o wysokiej koncentracji upraw ryżu. Obszary o intensywnej uprawie ryżu wykazują wyższą sezonową i długoterminową zmienność poziomów stężenia CH_4 w porównaniu z innymi obszarami. Zmiany w praktykach uprawy ryżu wpływają bezpośrednio na sezonowe emisje CH_4. Korzystanie z wysokiej rozdzielczości spektrometru TROPOMI na pokładzie satelity Sentinel-5P pozwala na monitorowanie poziomów stężenia CH_4 w atmosferze pochodzącego z upraw ryżu. W badaniach skoncentrowano się na regionach Azji Południowo-Wschodniej oraz obszarach wzdłuż rzeki Missisipi w USA, co pozwoliło na rozróżnienie emisji CH_4 pochodzących z upraw ryżu od innych źródeł. Emisje porównano także ze zmianami w skali globalnej. Badania potwierdziły wzrost i sezonową zmienność poziomów stężenia CH_4 w atmosferze w regionach upraw ryżu, co świadczy o wpływie praktyk rolniczych na emisje tego gazu.

3.2. Analiza przestrzennego rozkładu emisji CH_4 do atmosfery pochodzącego z hodowli zwierząt oraz analiza globalnych trendów w populacji bydła i ich wpływu na emisje CH_4.

Hipoteza badawcza zakłada, że instrument TROPOMI nie jest wystarczający do monitorowania poziomów stężenia CH_4 z rozproszonych źródeł, takich jak fermentacja jelitowa i gospodarowanie odchodami zwierząt, co wymaga zastosowania modelowania matematycznego opartego na populacji zwierząt i wskaźnikach emisji CH_4. Wzrost globalnej populacji bydła jest silnie skorelowany ze wzrostem emisji CH_4, przy czym zależność ta jest modyfikowana przez strukturę zwierząt i metody hodowli. W Publikacji III wykonano analizę czasowych trendów w populacji bydła od 1961 do 2020 roku oraz zbadano korelację między populacją bydła a emisjami CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt. Badania wykazały zróżnicowanie regionalne w zależności od praktyk hodowlanych oraz poziomu rozwoju gospodarczego. Ponadto w Publikacji IV przeprowadzono dokładne badanie przestrzennego rozkładu emisji CH_4 z hodowli zwierząt w Polsce. Zgodnie z oczekiwaniami, obszary gmin o większej gęstości populacji zwierząt wykazują wyższe emisje CH_4, ponieważ zmiany w produkcji zwierzęcej wpływają zarówno na liczbę zwierząt, jak i na wskaźniki emisji CH_4. Oszacowanie emisji CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt przeprowadzono na podstawie danych z Powszechnego Spisu Rolnego 2010 i 2020 prowadzonego w Polsce przez Główny Urząd Statystyczny (GUS). Badania dostarczyły szczegółowych danych na temat zmian w populacji zwierząt gospodarskich oraz związanych z tym zmian w emisjach CH_4, co jest kluczowe dla zrozumienia dynamiki emisji i rozwijania strategii redukcji emisji CH_4.

4. Materiały i metody badań

W niniejszym rozdziale omówiono metodykę badawczą w czterech publikacjach, które są przedmiotem rozprawy doktorskiej. W związku z analitycznym charakterem pracy, metodyka obejmowała kilka kluczowych etapów. Najpierw określono cele i hipotezy badawcze, a także wybrano odpowiednie podejście badawcze. Skupiono się na analizie emisji CH_4 z uprawy ryżu i hodowli bydła, korzystając z danych satelitarnych i statystycznych. Pozyskano dane z satelitów oraz z baz danych dotyczących produkcji rolniczej. Skupiono się na regionach i krajach o znaczących emisjach CH_4. Wykonano analizy danych satelitarnych z misji Sentinel-5P oraz zastosowano metody statystyczne do analizy danych historycznych dotyczących hodowli bydła. Skoncentrowano się na badaniu trendów czasowych, porównywaniu grup krajów i identyfikacji zmiennych związanych z emisją CH_4. Na podstawie przeprowadzonych badań sformułowano wnioski dotyczące emisji CH_4 z sektora rolniczego, uwzględniając zarówno długoterminowe, jak i sezonowe trendy.

4.1. Materiały badawcze

Materiały badawcze wykorzystane w publikacjach dotyczących emisji CH_4 z upraw ryżu oraz zmian populacji bydła pochodzą z różnych źródeł. W przypadku badań nad emisją CH_4 z upraw ryżu, głównym źródłem danych były obserwacje satelitarne z misji Sentinel-5P, które dostarczają pomiarów poziomów stężenia GHG w atmosferze. Dane dotyczące upraw ryżu, takie jak zbiory i plon, pochodzą z baz danych organizacji rolniczych lub statystyk rządowych krajów, w których prowadzono badania.

W przypadku badań nad zmianami w populacji bydła, źródłem danych były bazy danych dotyczące produkcji zwierzęcej, takie jak statystyki rolnicze krajów objętych badaniem, bazy danych międzynarodowych organizacji rolniczych oraz inne źródła związane z produkcją i hodowlą zwierząt. Dane te umożliwiły przeprowadzenie analizy trendów w populacji bydła na przestrzeni lat oraz oszacowanie emisji CH_4 związanej z hodowlą zwierząt.

Tabela 1 zawiera podsumowanie materiałów wykorzystanych w Publikacjach I, II, III i IV wraz z informacjami na temat jednostek miary, w których dane są prezentowane, przedziału czasowego dla wykonywanych badań oraz źródeł danych.

Tabela 1. Materiały badawcze w poszczególnych publikacjach.

Materiały	Jednostki	Okres badawczy	Źródło
	Publikacja I		
Kraje z wysokimi emisjami CH_4 z upraw ryżu	% całkowitych emisji	2019	FAOSTAT
Zbiory i plony ryżu	% całkowitej powierzchni	2005	EarthStat
Emisje GHG z pól uprawnych	Mg CO_2e rok^{-1}	2000	EarthStat
Pomiary CH_4 Sentinel-5P	średnie poziomy stężenia CH_4 w powietrzu (ppb)	2019 – 2021	Google Earth Engine
	Publikacja II		
Zbiory i plony ryżu	%; ha; 1000 ton; tony ha^{-1}	2005	EarthStat
Miasta świata	liczba ludności	2020	Esri Data and Maps
Pomiary CH_4 Sentinel-5P	średnie poziomy stężenia CH_4 w powietrzu (ppb)	2019 – 2022	Google Earth Engine
	Publikacja III		
Populacja bydła	sztuki	1961 – 2020	FAOSTAT
Maszyny rolnicze	sztuki	1961 – 2020	FAOSTAT
Populacja ogółem	liczba ludności	1961 – 2020	FAOSTAT
Procent ludności na wsiach	%	1961 – 2020	FAOSTAT
Łąki i pastwiska	1000 ha	1961 – 2020	FAOSTAT
Grunty uprawne	1000 ha	1961 – 2020	FAOSTAT
Spożycie mleka	l per capita rok^{-1}	1961 – 2020	FAOSTAT
Wydajność mleczna	hektogram rok^{-1}	1961 – 2020	FAOSTAT
Spożycie wołowiny	g per capita rok^{-1}	1961 – 2020	FAOSTAT
Spożycie mięsa	g per capita rok^{-1}	1961 – 2020	FAOSTAT
PKB	per capita (US$)	1961 – 2020	World Bank
Eksport/Import	US$	1961 – 2020	World Bank
Wskaźniki emisji (EF)	kg CH_4 na sztukę bydła^{-1} rok^{-1}	2006	IPCC 2006
	Publikacja IV		
Populacja bydła, trzody chlewnej i drobiu	sztuki	2010; 2020	GUS - Bank Danych Lokalnych
Użytki rolne	ha	2010; 2020	GUS - Bank Danych Lokalnych
Wskaźniki emisji (EF)	kg CH_4 na sztukę bydła^{-1} rok^{-1}	2010; 2020	Krajowy Raport Inwentaryzacyjny (NIR 2022)

4.2. Metody badawcze

W ramach rozprawy doktorskiej zastosowano różnorodne metody do badania emisji CH_4 ze źródeł rolniczych. Analiza danych satelitarnych z instrumentu TROPOMI na pokładzie satelity Sentinel-5P pozwoliła na ocenę przestrzenno-czasowych zmian poziomów stężenia CH_4 oraz analizę długoterminowych i sezonowych trendów w emisjach z upraw ryżu. W badaniach nad zmianami w populacji bydła wykorzystano metody statystyczne do analizy danych historycznych dotyczących hodowli zwierząt oraz emisji CH_4. Przeprowadzono również kompleksową analizę emisji CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt na podstawie danych z Powszechnego Spisu Rolnego oraz Krajowego Raportu Inwentaryzacyjnego. Wyniki analizy pozwoliły na ocenę zmian emisji CH_4 na poziomie gmin i województw między 2010 a 2020 rokiem, co umożliwiło dokładne zbadanie przestrzennego rozkładu emisji.

Celem Publikacji I był wybór krajów o wysokich emisjach CH_4 z upraw ryżu oraz analiza danych z FAOSTAT Database i EarthStat. Przeprowadzono również analizę danych satelitarnych Sentinel-5P (2019-2021), wyznaczono średnie poziomy stężenia CH_4 oraz zastosowano analizę regresji liniowej. Publikacja II miała na celu analizę sezonowych i długoterminowych zmian poziomów stężenia CH_4 w regionach uprawy ryżu. Cel ten zrealizowano wykorzystując dane satelitarne Sentinel-5P (2019-2022) oraz przeprowadzając analizę regresji i testy Manna-Kendalla. Publikacja III koncentrowała się na analizie globalnych trendów populacji bydła i ich wpływu na emisje CH_4. Przeprowadzono analizę danych historycznych (1961-2020), gdzie do modelowania matematycznego zastosowano metodę IPCC 2006 Tier 1, natomiast do analiz statystycznych użyto analizę skupień oraz analizę składowych głównych (PCA). Modelowanie matematyczne emisji CH_4 bazowało na wzorze:

$$Em_i = Ef_i \cdot A_i$$

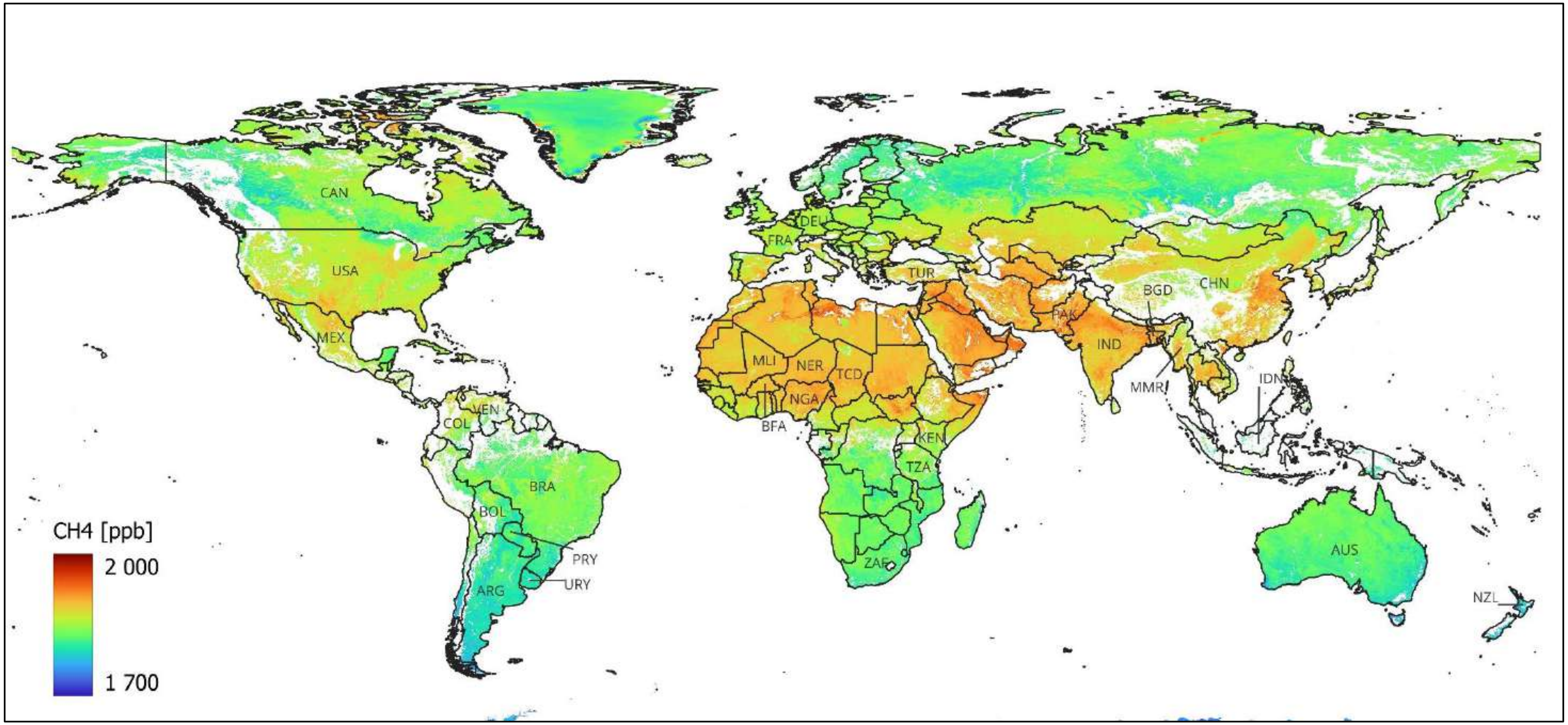
gdzie Em_i oznacza całkowite emisje CH_4 (Gg CH_4 rok^{-1}), Ef_i – wskaźnik emisji dla bydła (kg CH_4 na sztukę$^{-1}$ rok^{-1}), A_i – populację bydła w danym kraju.

Zbadanie przestrzennego rozkładu emisji CH_4 z hodowli zwierząt w Polsce na poziomie gmin (2010 i 2020) było celem Publikacji IV. Bazując na danych z Powszechnego Spisu Rolnego oraz wskaźnikach emisji CH_4 z Krajowego Raportu Inwentaryzacyjnego (NIR 2022) wykonano modelowanie matematyczne przestrzennej emisji CH_4 z fermentacji jelitowej i zarządzania odchodami zwierząt w programie QGIS 3.18.

5. Najważniejsze wyniki badań i dyskusja

W niniejszych badaniach zastosowano nowoczesne technologie satelitarne, w tym dane ze spektrometru TROPOMI na pokładzie satelity Sentinel-5P, do analizy długoterminowych i sezonowych zmian poziomów stężenia CH_4 w atmosferze, szczególnie w regionach o wysokiej koncentracji upraw ryżu. Oprócz tego, przeanalizowano przestrzenny rozkład poziomów stężenia CH_4 pochodzącego z hodowli zwierząt w Polsce oraz globalne trendy w populacji bydła i ich wpływ na emisje CH_4. Publikacje I i II miały za zadanie ustalić, czy dane satelitarne Sentinel-5P i spektrometru TROPOMI są w stanie wykrywać zmiany poziomów stężenia CH_4 w regionach o wysokiej koncentracji upraw ryżu. Wykazano, że obszary o intensywnej uprawie ryżu charakteryzują się wyższą sezonową i długoterminową zmiennością poziomów stężenia CH_4 w porównaniu z innymi regionami. Zmiany w praktykach uprawy ryżu mają bezpośredni wpływ na sezonowe emisje CH_4. Monitorowanie emisji za pomocą wysokiej rozdzielczości spektrometru TROPOMI na pokładzie satelity Sentinel-5P umożliwia śledzenie tych zmian, co potwierdza wpływ intensywnych praktyk rolniczych na emisje CH_4. W Publikacjach III i IV przeprowadzono analizę przestrzennego rozkładu emisji CH_4 w Polsce pochodzących z hodowli zwierząt oraz analizę globalnych trendów w populacji bydła i ich wpływu na emisje CH_4. Analizy te były konieczne, ponieważ jak ustalono, instrument TROPOMI nie jest wystarczający do monitorowania poziomów stężenia CH_4 z rozproszonych źródeł, takich jak fermentacja jelitowa i gospodarowanie odchodami zwierząt. Dlatego zastosowano modelowanie matematyczne oparte na populacji zwierząt i wskaźnikach emisji CH_4. Mapa na Rysunku 1 przedstawia globalne poziomy stężenia CH_4 w atmosferze w 2020 roku, oznaczone w częściach na miliard (ppb). Na mapie zaznaczono również kraje, które mają największe emisje CH_4 pochodzące z hodowli zwierząt. Analiza zmian w populacji bydła i emisjach CH_4 w tych krajach została opisana w Publikacji III. Regiony o wysokich poziomach stężeniach CH_4 to Afryka Północna oraz Azja Południowa i Południowo-Wschodnia. Kraje takie jak Czad (TCD), Niger (NER), Mali (MLI), Burkina Faso (BFA) i Nigeria (NGA) wykazują wysokie poziomy stężenia CH_4, co może wynikać z prowadzenia intensywnej hodowli zwierząt oraz rolnictwa, ale także z działalności związanej z produkcją gazu ziemnego. Wydobycie, przetwarzanie, transport i spalanie gazu ziemnego przyczyniają się do wysokich poziomów stężenia CH_4 w atmosferze. Natomiast Indie (IND), Pakistan (PAK), Bangladesz (BGD), Mjanma (MMR) i Chiny (CHN) wykazują wysokie poziomy stężenia

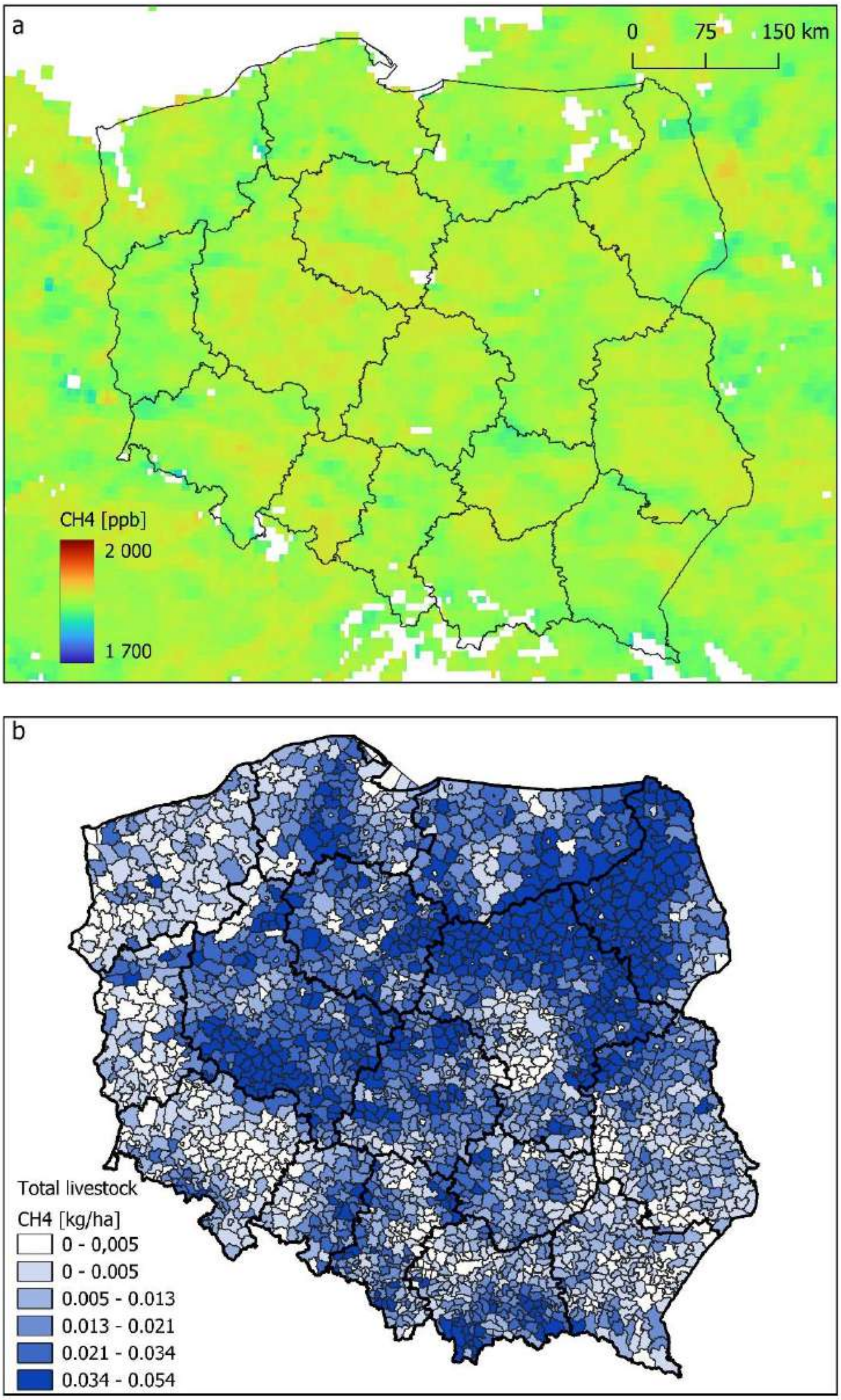
CH_4, co jest związane z intensywnymi uprawami ryżu. Kraje Ameryki Południowej takie jak Brazylia (BRA), Argentyna (ARG) i Boliwia (BOL) charakteryzują się średnimi poziomami stężenia CH_4, mimo dużej skali hodowli bydła. USA (USA) i Meksyk (MEX) są jednymi z większych emitentów CH_4 pochodzącego z fermentacji jelitowej i gospodarowania odchodami zwierząt, ale także z przemysłu naftowego i gazowego, mimo, że wyniki tego nie podkreślają. Ponadto Australia (AUS) i Nowa Zelandia (NZL) mają niskie poziomy stężenia CH_4, mimo, że są wśród 30 krajów o największej emisji CH_4 pochodzącej z hodowli zwierząt.



Rysunek 1. Globalne poziomy stężenia CH_4 w atmosferze w 2020 roku (ppb). Opracowanie własne na podstawie danych satelitarnych Sentinel-5P, dostępnych na Google Earth Engine https://earthengine.google.com/ (dostęp 08.06.2024 r.).

Wzrost globalnej populacji bydła jest silnie skorelowany ze wzrostem emisji CH_4, przy czym zależność ta jest modyfikowana przez strukturę zwierząt i metody hodowli. Instrument TROPOMI nie wystarcza do monitorowania rozproszonych emisji CH_4, dlatego konieczne jest zastosowanie modelowania matematycznego opartego na populacji zwierząt i wskaźnikach emisji.

Na Rysunku 2a przedstawiona jest mapa Polski pokazująca regionalne różnice w poziomach stężenia CH_4 w atmosferze w 2020 r. mierzone za pomocą instrumentu TROPOMI na pokładzie satelity Sentinel-5P, które są związane z różnymi źródłami emisji, zarówno naturalnymi, jak i antropogenicznymi, w tym z rolnictwem, przemysłem i innymi sektorami. Rysunek 2b przedstawia modelowane dane emisji CH_4 pochodzące z hodowli zwierząt na poziomie gmin w Polsce w 2020 r., które zostały oszacowane na podstawie danych z GUS oraz NIR. Modelowanie uwzględniało emisje z różnych kategorii zwierząt gospodarskich oraz stosowane metody gospodarowania odchodami zwierząt. Mapa pozwala na zobrazowanie intensywności emisji CH_4 z fermentacji jelitowej i gospodarowania odchodami zwierząt na jednostkę powierzchni gminy. Porównanie obu rysunków pozwala na ocenę zgodności pomiędzy rzeczywistymi pomiarami stężenia CH_4 w atmosferze a szacowanymi emisjami na podstawie danych statystycznych i modeli emisji. Rozmieszczenia maksymalnych poziomów stężenia CH_4 oraz maksimów modelowanej emisji CH_4 są tylko w pewnym stopniu podobne na obu mapach. Rozbieżności mogą wskazywać na potrzebę uwzględnienia dodatkowych źródeł emisji CH_4 w danych satelitarnych.

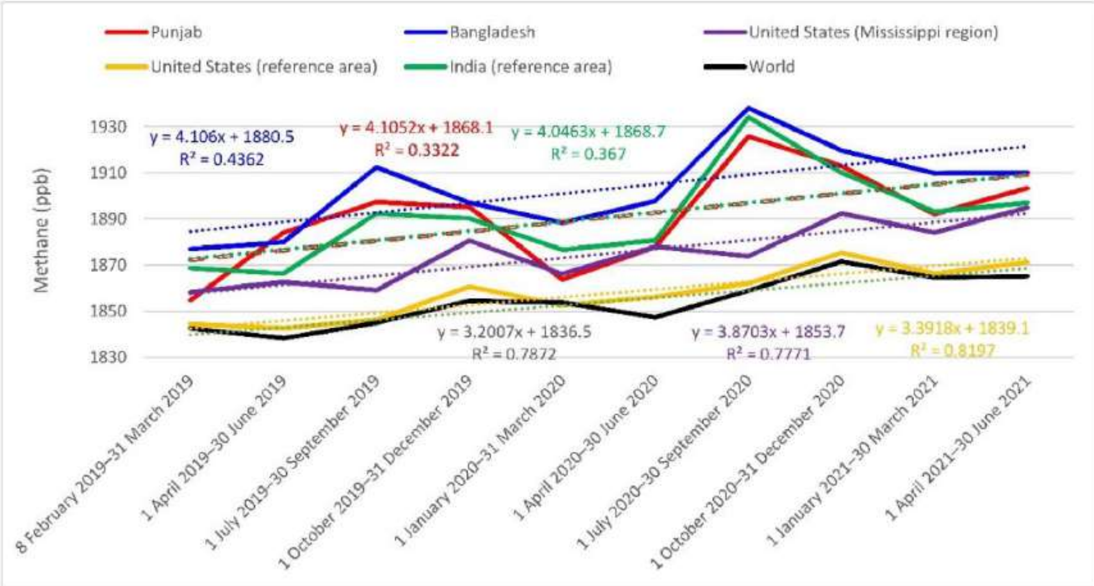


Rysunek 2. Poziomy stężenia CH_4 w Polsce w 2020 r. (ppb) oraz przestrzenny rozkład całkowitych emisji CH_4 z hodowli zwierząt (kg ha^{-1}) w 2020 r. **a.** Opracowanie własne na podstawie danych satelitarnych Sentinel-5P, dostępnych na Google Earth Engine (https://earthengine.google.com/). **b.** Opracowanie własne na podstawie danych z GUS - Bank Danych Lokalnych oraz Krajowego Raportu Inwentaryzacyjnego (NIR 2022) z Publikacji IV.

Poniżej przedstawiono szczegółowe wyniki badań z publikacji stanowiących podstawę rozprawy doktorskiej.

5.1. Publikacja I

Badania zaprezentowane w Publikacji I pozwoliły na zaobserwowanie długoterminowego wzrostu poziomów stężenia CH_4 na badanych obszarach (Rysunek 3).



Rysunek 3. Zmiany czasowe poziomów stężenia CH_4 w wybranych krajach/regionach oraz na całym świecie (ograniczonych do szerokości geograficznych między 60°S a 60°N) na podstawie danych z Sentinel-5P (ppb) oraz równania regresji przedstawiające zależności między poziomami stężenia CH_4 (y) a kolejnymi 3-miesięcznymi okresami (x). Rysunek pochodzi z Publikacji I.

Zmiany te były podobne dla większości regionów Azji Południowo-Wschodniej. Analiza regresji potwierdziła średni roczny wzrost na około 16 ppb, co przekłada się na około 4 ppb za każdy trzymiesięczny okres. W przypadku regionu Missisipi, średni roczny wzrost wyniósł około 15,5 ppb (3,87 ppb na kwartał). Światowy wzrost emisji CH_4 (ograniczony do szerokości geograficznych między 60° S a 60° N) wyniósł 12,8 ppb rocznie (3,20 ppb na kwartał), a więc był niższy w porównaniu z obszarami uprawy ryżu. Wyniki te są zgodne z danymi z lokalizacji Total Carbon Column Observing Network (TCCON) (Sha i in., 2021). Sezonowe zmiany poziomów stężenia CH_4 charakteryzowały się najniższymi poziomami na początku roku, a najwyższymi w trzecim kwartale. Jest to związane z intensywnym wzrostem ryżu, który według kalendarza upraw rozpoczyna się późną wiosną i kończy jesienią (Zhang i in., 2020). Wyraźna sezonowość emisji była widoczna w Bangladeszu, zwłaszcza w okresie wzrostu ryżu znanym jako „aman”, trwającym od kwietnia do listopada lub grudnia (Shelley i in., 2016). Maksymalne poziomy stężenia CH_4 zaobserwowano w październiku. Dodatkowo, wpływ uprawy ryżu na sezonową zmienność poziomów stężenia CH_4 w atmosferze potwierdzają obserwacje z regionów, gdzie ryż nie jest uprawiany. Na przykład, w południowo-zachodnich i południowo-wschodnich częściach Bangladeszu, które głównie są zalesione (Uddin i in., 2019), stwierdzono niższe poziomy stężenia CH_4 oraz mniejszą zmienność sezonową w porównaniu z innymi częściami kraju, gdzie uprawia się ryż. Podobny wzorzec sezonowych zmian poziomów stężenia CH_4 obserwowano w regionie Missisipi, gdzie wyższe poziomy stężenia CH_4 i większe amplitudy sezonowe występują na obszarach z uprawami ryżu w porównaniu z sąsiednimi terenami, na których ryż nie jest uprawiany.

Większość korelacji między szacowanymi emisjami gazów cieplarnianych a uśrednionymi poziomami stężenia CH_4 była, zgodnie z oczekiwaniami, dodatnia. Najsilniejsze korelacje zaobserwowano dla regionów takich jak Hubei i Hunan w Chinach, Pendżab w Indiach, Kambodża, Filipiny i Nepal, ze średnimi współczynnikami korelacji wynoszącymi od 0,48 do 0,79. Podobne zależności między poziomami stężenia CH_4 w atmosferze a procentowym udziałem pól ryżowych w Azji Południowo-Wschodniej zaobserwowano również w badaniu Zhanga i in. (2020), co potwierdza możliwość obserwacji emisji CH_4 z pól ryżowych przez instrumenty satelitarne.

5.2. Publikacja II

Długoterminowy wzrost poziomów stężenia CH_4 zaobserwowano we wszystkich analizowanych regionach. Średni roczny wzrost poziomów stężenia CH_4 w atmosferze na obszarach o intensywnej uprawie ryżu był zróżnicowany – najwyższy odnotowano w Biharze w Indiach (19,6 ppb), a najniższy w Irawadi (ang. *Ayeyarwady*) w Mjanmie (3,7 ppb). Różnice mogą wynikać z odmiennych krajowych trendów w produkcji ryżu. W Indiach i Bangladeszu, gdzie produkcja ryżu wzrasta, stwierdzono wyższy wzrost poziomów stężenia CH_4, w przeciwieństwie do Mjanmy i Jawy, gdzie odnotowuje się spadek produkcji ryżu od 2018 roku (FAOSTAT). Globalny wzrost poziomów stężenia CH_4 od lutego 2019 do stycznia 2022 roku wyniósł średnio 15,6 ppb rocznie, co jest zgodne z pomiarami NOAA Global Monitoring Laboratory (2022), gdzie współczynnik regresji wyniósł 1,3 ppb miesięcznie. W niektórych regionach, szczególnie w Indiach i Bangladeszu, odnotowano wyższy wzrost poziomów stężenia CH_4 w porównaniu ze średnią globalną. Natomiast w Irawadi (Mjanma) i na Jawie (Indonezja) stwierdzono stosunkowo niskie tempo wzrostu tych emisji. Różnice w dynamice emisji CH_4 na poziomie regionalnym mogą być związane z różnorodnością praktyk upraw ryżu oraz z regionalnymi politykami zarządzania zasobami wodnymi i rolnictwem (Lan i in., 2022).

Obszary referencyjne, bez intensywnej uprawy ryżu, niekiedy wykazywały podobne poziomy stężenia CH_4 do głównych regionów upraw. Na przykład, w Gudżaracie i Radżastanie (Indie), średnie poziomy stężenia CH_4 były zbliżone do innych części kraju, co jest efektem lokalnego wydobycia węgla brunatnego, odpowiadającego za 11% antropogenicznych emisji CH_4 (Sadavarte i in., 2021; Saunois i in., 2020). Kolejnym przykładem jest Junnan w południowych Chinach, gdzie zróżnicowane naturalne warunki klimatyczne i biologiczne sprzyjają wyższym emisjom CH_4 (Gong & Shi, 2021; Zhou i in., 2018).

Ponadto przeprowadzono analizę sezonową szeregów czasowych na podstawie średnich ruchomych dla miesięcznych poziomów stężenia CH_4. Wyniki potwierdziły sezonową zmienność z najniższymi wartościami w lipcu (około 15,5 ppb) i najwyższymi w październiku. Analiza przeprowadzona dla Pendżabu, Biharu i Radżastanu wykazała znacznie wyższą różnicę poziomów stężenia CH_4 (47-58 ppb) w porównaniu z danymi globalnymi. Najwyższe stężenia atmosferycznego CH_4 notowane były we wrześniu i październiku, co odpowiada okresowi intensywnego wzrostu ryżu w północnych Indiach. Podobne obserwacje dotyczące maksymalnych emisji CH_4 w sezonie letnim w Indiach i Chinach uzyskano w badaniach Zhanga i in. (2016) oraz Ito i in. (2022).

5.3. Publikacja III

W 1961 roku globalna populacja bydła szacowana była na około 942 miliony sztuk, natomiast w 2020 roku liczba ta wzrosła do około 1523 milionów sztuk. Średnioroczny wzrost wyniósł około 8,3 miliona, co dobrze opisuje model liniowy ze współczynnikiem determinacji R^2 = 0,95. Zgodnie z przewidywaniami, wzrost liczby bydła korelował ze wzrostem zagęszczenia bydła, wyrażonego jako liczba sztuk bydła na 1000 hektarów gruntów rolnych. Jednakże, wzrost liczby bydła o 62% w analizowanym okresie był wyższy niż wzrost stosunku liczby bydła do gruntów rolnych, który wynosił około 51%. Liczba sztuk bydła przypadająca na 1000 osób wykazywała tendencję spadkową (R^2 = 0,98), zmniejszając się z 307 do 194, co stanowi spadek o około 37%. Średnioroczny wzrost globalnych emisji CH_4 w badanym okresie wyniósł 0,34 miliona ton. Wzrost liczby bydła o jedną sztukę wiązał się ze średnim rocznym wzrostem emisji CH_4 o 42,7 kg.

Trendy dotyczące liczby bydła oraz jego stosunku do gruntów rolnych i liczby ludności wykazywały znaczące różnice między poszczególnymi krajami. W Czadzie odnotowano najwyższy wzrost pogłowia bydła, który wzrósł o 488% w ostatniej dekadzie badanego okresu w porównaniu z pierwszą dekadą. Podobne, choć nieco mniejsze wzrosty zaobserwowano w Boliwii i Burkina Faso, gdzie liczba bydła wzrosła o ponad 300%, natomiast w Brazylii, Nigrze, Paragwaju i Ugandzie wzrost ten oscylował w granicach 200-300%. Większość badanych krajów wykazała wzrost pogłowia bydła, jednak Niemcy, Francja i USA odnotowały spadki, odpowiednio o 33%, 9% i 14%. Powierzchnia gruntów rolnych pozostała relatywnie stabilna przez cały okres, z tendencją do wyższego stosunku liczby bydła do powierzchni użytków rolnych w ostatniej dekadzie (2011-2020) w porównaniu z pierwszą dekadą (1961-1970).

Aby zrozumieć globalne trendy w zmianach pogłowia bydła, przeprowadzono analizę skupień, która wyodrębniła trzy główne grupy krajów o podobnych wzorcach. Pierwsza grupa, składająca się z czterech krajów z Afryki Środkowej i Pakistanu z Azji Południowej, charakteryzowała się znacznym wzrostem pogłowia bydła, szczególnie w ostatnich dwóch dekadach. Ciekawym przypadkiem był Czad, który wykazał najwyższy wzrost w badanym okresie, osiągając szczyt w latach 1991-2000. Druga grupa, obejmująca kraje z Ameryki Południowej, południowej części Ameryki Północnej, Azji Południowo-Wschodniej i Afryki Środkowej, odnotowała stosunkowo stabilny wzrost populacji bydła przez cały okres badań, ze znacznie wyższym wzrostem w pierwszej połowie okresu badawczego. W tych krajach zaobserwowano również znaczny wzrost populacji ludzkiej, co wiązało się ze wzrostem spożycia mięsa i mleka, choć na niższym poziomie niż w krajach rozwiniętych (Revell, 2015; Stoll-Kleemann & O'Riordan, 2015). Trzecia, najliczniejsza grupa, skupiała głównie kraje wysoko rozwinięte z różnych regionów świata, gdzie początkowy wzrost liczby bydła ustabilizował się w latach 1981-2020.W analizie korelacji przeprowadzonej w celu oceny związków między pogłowiem bydła a różnymi zmiennymi opisującymi produkcję rolną, konsumpcję żywności oraz warunki ekonomiczne wykorzystano dane roczne z lat 1961-2020. W przypadku krajów z pierwszej i drugiej grupy, a także Czadu, zaobserwowano silne, dodatnie korelacje między liczbą bydła a populacją ludności, ze współczynnikami korelacji w zakresie od 0,85 do 0,99. Wskaźniki te sugerują bliski związek wzrostu pogłowia bydła z dynamiką wzrostu populacji ludzkiej w tych regionach. Dodatkowo, liczba bydła wykazywała silną pozytywną korelację z PKB na mieszkańca i powierzchnią gruntów rolnych, a także negatywną korelację z odsetkiem ludności wiejskiej, co odzwierciedlało urbanizację i zmiany w strukturze społeczno-gospodarczej. Wnioski te były konsekwentne dla większości krajów z pierwszej i drugiej grupy. Jednakże, inne korelacje, takie jak związek między liczbą bydła a wydajnością mleczną na zwierzę, były mniej jednoznaczne, obserwowane tylko w około dwóch trzecich krajów tych grup. W trzeciej grupie, obejmującej głównie kraje wysoko rozwinięte, korelacje te były mniej spójne, wykazując zarówno pozytywne, jak i negatywne wartości.

Różnice między grupami krajów wskazują na zróżnicowany wpływ globalnych trendów w hodowli bydła, co może wynikać z odmiennych praktyk rolniczych, polityk rządowych i poziomu rozwoju gospodarczego. W krajach rozwijających się, gdzie zaobserwowano silną korelację między liczbą bydła a populacją, wzrost hodowli bydła często nadąża za wzrostem ludności, co jest związane z rosnącym zapotrzebowaniem na produkty mleczne i mięsne. Natomiast w krajach wysoko rozwiniętych stabilizacja lub spadek liczby bydła może odzwierciedlać wyższą efektywność produkcji, zmiany w diecie społeczności lub zwiększone wykorzystanie technologii w produkcji rolniczej.

5.4. Publikacja IV

Całkowite emisje CH_4 z hodowli zwierząt w Polsce nieznacznie wzrosły, z poziomu 528 Gg w 2010 roku do 557 Gg w 2020 roku. Zarówno gospodarstwa hodowlane, jak i emisje, wykazywały silne zróżnicowanie pod względem regionalnym. W wyniku przeprowadzonej analizy zaobserwowano, że emisje oscylowały między 8 a 106 Gg CH_4 w 16 województwach. W roku 2020 emisje CH_4 pochodzące od bydła niemlecznego wzrosły o 23,4%. Najwyższe emisje odnotowano w województwach wielkopolskim, mazowieckim, podlaskim i kujawsko-pomorskim.

W przypadku bydła mlecznego wzrost emisji do roku 2020 nie był znaczący – wyniósł ok. 1,6%, co było wynikiem zmniejszającego się pogłowia. Emisje dominowały w północno-wschodniej Polsce, zwłaszcza w województwach podlaskim, mazowieckim, wielkopolskim i warmińsko-mazurskim. Od momentu przystąpienia Polski do Unii Europejskiej w 2004 roku produkcja mleka w Polsce znacząco wzrosła, pod wpływem regulacji Unii Europejskiej oraz Wspólnej Polityki Rolnej. Średnia wydajność mleka wzrosła z 4487 w 2010 roku do 5946 litrów na krowę rocznie w 2020 roku, za sprawą inwestycji w wysokiej jakości pasze oraz modernizacji obór (Kowalska i in., 2019). Z drugiej jednak strony, wprowadzenie limitów produkcji mleka zmusiło mniejszych producentów do rezygnacji z działalności lub przejścia na rolnictwo częściowo oparte na dotacjach.

Emisje CH_4 związane z produkcją trzody chlewnej zmniejszyły się o 34,0% do 2020 roku. Główną przyczyną było wprowadzenie czerwonych stref afrykańskiego pomoru świń (ASF, ang. *african swine fever*) oraz nieopłacalność produkcji prosiąt i tuczników, wynikająca z niskiej zdolności reprodukcyjnej polskiego stada macierzystego, znaczących strat prosiąt oraz wysokich wskaźników konwersji pasz (Dors i in., 2013). W rezultacie populacja świń w Polsce zmniejszyła się, zwłaszcza w przypadku mniejszych gospodarstw (Pepliński, 2023). Dlatego większość produkcji trzody chlewnej pochodzi z dużych ferm przemysłowych zlokalizowanych w określonych regionach Polski, głównie w województwach wielkopolskim, mazowieckim, łódzkim i kujawsko-pomorskim.

W porównaniu do pozostałych kategorii zwierząt, emisje związane z drobiem były minimalne – poniżej 1,1%. Niemniej jednak, ze względu na dynamiczny wzrost populacji drobiu, głównie za sprawą sprzedaży drobiu na rynkach zagranicznych, emisje w 2020 roku były wyższe o 28,7% niż w 2010 roku. Ze względu na wysoką różnorodność regionalną dużych ferm drobiu w Polsce, emisje mają charakter punktowy na poziomie gminnym. Najwyższe emisje CH_4 zaobserwowano w gminach na terenie województw wielkopolskiego, śląskiego, mazowieckiego i zachodniopomorskiego.

Najniższe emisje CH_4 zaobserwowano w południowo-wschodniej i południowo-zachodniej części Polski. Powodem tego jest przewaga gospodarstw zajmujących się produkcją roślinną, a także liczne mniejsze gospodarstwa o powierzchni poniżej 5 hektarów (Małopolski Ośrodek Doradztwa Rolniczego, 2020; Poczta i Bartkowiak, 2012). Dodatkowym czynnikiem ograniczającym jest rozwój urbanizacji, potencjalne możliwości zatrudnienia w większych miastach, a także zmiana z produkcji rolnej na turystykę w regionach górskich (Bański, 2010; Wysocka-Czubaszek i in., 2018).

Wielkość emisji z fermentacji jelitowej zależy od populacji zwierząt oraz czynników wpływających na wskaźniki emisji CH_4 dla poszczególnych kategorii zwierząt. Według raportu NIR 2022 dla Polski, współczynniki emisji CH_4 dla bydła wzrosły w związku ze zwiększającym się spożyciem energii brutto do 2020 roku. Emisje

CH_4 z zarządzania odchodami generowane są głównie przez bydło, zwłaszcza podczas laktacji, oraz trzodę chlewną. Wielkość emisji ponownie zależy przede wszystkim od populacji zwierząt oraz wskaźników emisji, które opierają się na zawartości substancji lotnych w odchodach, systemach gospodarowania odchodami, a także różnicach w emisjach spowodowanych temperaturą w różnych regionach świata. (IPCC 2006). Do 2020 roku wskaźniki emisji dla gospodarowania odchodami u bydła i trzody chlewnej w Polsce uległy zmniejszeniu. Malejący trend emisji CH_4 z gospodarowania odchodami wiąże się z dynamicznym spadkiem liczby gospodarstw hodowlanych oraz zmianami w systemach przechowywania odchodów zwierzęcych. Według raportu NIR 2022, w Polsce bardziej powszechne są systemy gospodarowania odchodami w formie stałej niż płynnej lub pastwiskowej, co wynika z niższych kosztów inwestycyjnych. Taki wybór prowadzi do mniejszej ilości CH_4 wytwarzanej w warunkach aerobowych.

6. Odpowiedź na postawione w rozprawie problemy badawcze oraz wnioski

6.1. Wykorzystanie danych satelitarnych Sentinel-5P i spektrometru TROPOMI do analizy długoterminowych i sezonowych zmian poziomów stężenia CH_4 w atmosferze w regionach o wysokiej koncentracji upraw ryżu.

Dane satelitarne Sentinel-5P i spektrometru TROPOMI skutecznie wykrywają zmiany poziomów stężenia CH_4 w regionach o intensywnej uprawie ryżu. Obserwacje wykazały wyraźną sezonową i długoterminową zmienność poziomów stężenia CH_4 w tych obszarach, potwierdzając hipotezę badawczą. Obszary intensywnej uprawy ryżu wykazują wyższą sezonową i długoterminową zmienność poziomów stężenia CH_4 w porównaniu do innych regionów. Zmiany w praktykach uprawy ryżu mają bezpośredni wpływ na sezonowe emisje CH_4, co jest widoczne w pomiarach dla Azji Południowo-Wschodniej i regionu Missisipi w USA. Wykorzystanie wysokiej rozdzielczości spektrometru TROPOMI na pokładzie satelity Sentinel-5P pozwala na monitorowanie poziomów stężenia CH_4 w atmosferze, umożliwiając identyfikację trendów i zmian sezonowych. Wyniki badań wykazały wzrost i sezonową zmienność poziomów stężenia CH_4 w regionach upraw ryżu, co potwierdza skuteczność tej metody monitorowania.

6.2. Analiza przestrzennego rozkładu emisji CH_4 do atmosfery pochodzącego z hodowli zwierząt oraz analiza globalnych trendów w populacji bydła i ich wpływu na emisje CH_4.

Celem badawczym była analiza przestrzennego rozkładu poziomów stężenia CH_4 w atmosferze pochodzącego z hodowli zwierząt oraz globalnych trendów w populacji bydła i ich wpływu na emisje CH_4. Instrument TROPOMI, mimo swojej skuteczności w monitorowaniu ogólnych poziomów stężenia CH_4 w atmosferze, nie jest wystarczający do monitorowania emisji z rozproszonych źródeł, takich jak fermentacja jelitowa i gospodarowanie odchodami zwierząt. Wymaga to zastosowania modelowania matematycznego opartego na populacji zwierząt i wskaźnikach emisji CH_4. Wzrost globalnej populacji bydła jest silnie skorelowany ze wzrostem emisji CH_4. Analiza czasowych trendów w populacji bydła od 1961 do 2020 roku wykazała zróżnicowanie regionalne w zależności od praktyk hodowlanych oraz poziomu rozwoju gospodarczego. Wzrost liczby bydła prowadzi do zwiększenia emisji CH_4, co jest modyfikowane przez strukturę zwierząt i metody hodowli. Zgodnie z przewidywaniami, badania wykazały, że obszary gmin o większej gęstości populacji zwierząt w Polsce wykazują wyższe emisje

CH_4. Zmiany w produkcji zwierzęcej mają bezpośredni wpływ na populację zwierząt oraz wskaźniki emisji CH_4, co podkreśla znaczenie regionalnych strategii w redukcji emisji CH_4. Oszacowanie emisji CH_4 na podstawie danych z Powszechnego Spisu Rolnego 2010 i 2020 dostarczyło szczegółowych informacji na temat zmian w populacji zwierząt gospodarskich oraz związanych z tym zmian w emisjach CH_4. Wyniki te są ważne do opracowania strategii redukcji emisji CH_4 oraz do zrozumienia dynamiki emisji na poziomie lokalnym i globalnym. Badania wykazały istotne znaczenie modelowania matematycznego dla monitorowania i analizy zmian w emisji CH_4. Jest to kluczowe dla skutecznego zarządzania i redukcji tych emisji w kontekście globalnych zmian klimatycznych.

7. Podsumowanie rozprawy doktorskiej i perspektywy dalszych badań

Przedstawiona rozprawa doktorska dostarcza kompleksowej analizy emisji CH_4 z różnych źródeł rolniczych, w szczególności z upraw ryżu i hodowli zwierząt. Badania te są istotne dla zrozumienia dynamiki emisji CH_4 oraz dla opracowania strategii ich redukcji w kontekście globalnych zmian klimatycznych.

Dane satelitarne z instrumentu TROPOMI na pokładzie satelity Sentinel-5P potwierdziły skuteczność tej technologii w monitorowaniu emisji CH_4 ze skoncentrowanych źródeł, takich jak uprawa ryżu. Analizy przestrzenne i czasowe wykazały wyraźne wzorce sezonowej i długoterminowej zmienności poziomów stężenia CH_4. Zmiany w praktykach uprawy ryżu, takie jak zalewanie pól, mają bezpośredni wpływ na sezonowe emisje CH_4, co zostało potwierdzone przez dane z Sentinel-5P. Wyniki te potwierdzają, że dane z TROPOMI są wystarczająco precyzyjne do monitorowania zmian w poziomach stężenia CH_4 w regionach o wysokiej koncentracji upraw ryżu, co jest zgodne z hipotezą badawczą.

Analiza emisji CH_4 z hodowli zwierząt wykazała, że instrument TROPOMI nie jest wystarczający do precyzyjnego monitorowania emisji z rozproszonych źródeł, takich jak fermentacja jelitowa i gospodarowanie odchodami zwierząt. Dlatego też konieczne było zastosowanie modelowania matematycznego opartego na populacji zwierząt oraz wskaźnikach emisji CH_4.

Dalsze badania w zakresie monitorowania emisji CH_4 powinny skupić się na kilku strategicznych obszarach. Konieczne jest rozwijanie metod integrujących dane satelitarne z pomiarami naziemnymi oraz modelowaniem matematycznym. Takie podejście pozwoli na precyzyjne oszacowanie źródeł i wielkości emisji CH_4 oraz na ocenę wpływu różnych praktyk rolniczych na emisje CH_4. Należy rozwijać technologie satelitarne o wyższej rozdzielczości i lepszej zdolności wykrywania rozproszonych emisji CH_4. Instrumenty takie jak TROPOMI mogą być udoskonalane, aby lepiej radzić sobie z monitorowaniem emisji z tych źródeł. Dalsze badania powinny także koncentrować się na dokładniejszym modelowaniu emisji CH_4 z hodowli zwierząt. Należy uwzględniać różnorodność praktyk hodowlanych i regionalnych strategii gospodarowania odchodami zwierząt, aby lepiej zrozumieć wpływ tych czynników na emisje CH_4.

Wyniki badań nad emisjami CH_4 powinny być wykorzystywane do opracowywania polityk i strategii mających na celu redukcję emisji GHG. Wprowadzenie bardziej efektywnych metod zarządzania rolnictwem może znacząco przyczynić się do zmniejszenia emisji CH_4.

Ze względu na globalny charakter emisji CH_4, niezbędna jest współpraca międzynarodowa w zakresie badań i monitorowania emisji. Wymiana danych i doświadczeń między krajami może przyczynić się do bardziej skutecznej walki ze zmianami klimatu.

Podsumowując, rozprawa dostarcza istotnych informacji na temat emisji CH_4 z różnych źródeł rolniczych, podkreślając znaczenie zaawansowanych technologii satelitarnych i modelowania matematycznego w monitorowaniu i analizie tych emisji. Dalsze badania w tym zakresie są kluczowe dla skutecznego zarządzania emisjami CH_4 i walki z globalnymi zmianami klimatycznymi.

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Pozostały dorobek naukowy

Projekt naukowy

2024 2026	**Satellites to estimate CH_4 emissions from dairy farms in Northern Sweden** Post-doc, wykonawca SLU – Swedish University of Agricultural Sciences, Department of Agricultural Research for Northern Sweden, Umeå

Staże naukowe

2023	**Penn State: The Pennsylvania State University** Department of Animal Science Opiekun naukowy: prof. Alexander N. Hristov
2022	**SLU – Swedish University of Agricultural Sciences** Department of Agricultural Research for Northern Sweden, Umeå Opiekun naukowy**:** dr Mohammad Ramin

Konferencje i seminaria

2024	Biogas and Climate Friendly Agriculture Workshop, Polish and Danish Embassy, Warsaw University of Life Sciences - SGGW, Poland **Prelegentka podczas panelu dyskusyjnego**
2023	Dairy Nutrition Workshop, Hershey, PA. Penn State, The Pennsylvania State University
2023	The LII International Biometrical Colloquium, Polska Prezentacja: *Spatial analysis of agricultural methane emission at the municipality (LAU-2) level across Poland.* **Kozicka, K.**, Ollik, M., Wójcik-Gront, E.
2022	1th PhD Student's Conference at the University of Life Sciences in Lublin, Poland: „Environment-Plant-Animal-Product" Poster: *Spatial-temporal changes of atmospheric methane content from rice cultivation regions.* **Kozicka, K.**, Gozdowski, D., Wójcik-Gront, E.
2021	IV Konferencja Doktorantów pt. „Cztery Żywioły – współczesne problemy w naukach o życiu" Prezentacja: *Przestrzenno-czasowe zmiany zawartości metanu w atmosferze dla wybranych krajów i regionów o wysokiej emisji metanu z uprawy ryżu.* **Kozicka, K.**, Gozdowski, D., Wójcik-Gront, E.
2021	L Międzynarodowe Colloquium Biometryczne Prezentacja (współautor): *Trends in methane emissions from livestock farming.* Wójcik-Gront, E., **Kozicka, K.**

Certyfikowane kursy

2022	**Ruminant Nutrition - Digestion and Forage Chemistry** SLU – Swedish University of Agricultural Sciences, Umeå

Kopie publikacji składających się na rozprawę doktorską wraz z oświadczeniami współautorów

atmosphere

Article

Spatial-Temporal Changes of Methane Content in the Atmosphere for Selected Countries and Regions with High Methane Emission from Rice Cultivation

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Abstract: Irrigated and flooded rice is associated with methane (CH_4) emissions. CH_4 is one of the most important anthropogenic greenhouse gases (GHG) in the atmosphere. Nowadays, mapping CH_4 content at a global scale is possible using satellite sensors. Sample of such a sensor is TROPOspheric Monitoring Instrument (TROPOMI) placed on the Sentinel-5 Precursor (Sentinel-5P) satellite board. In this study, the evaluation of spatial-temporal changes in CH_4 content in the atmosphere for selected countries and regions with high CH_4 emissions from rice cultivation in 2019–2021 was performed. Visual evaluation of the spatial variability on CH_4 content for the total study period indicates higher CH_4 content for almost all areas with high rice concentration. This was confirmed by positive correlations between CH_4 content in the atmosphere and estimated GHG emissions from croplands analyzed separately for each studied country/region. In addition, seasonal changes in CH_4 content in the atmosphere were observed. The lowest CH_4 content was observed at the beginning of the year (for the first quarter of the year) and the highest for the third quarter of the year. Moreover, a long-term increase in CH_4 was noticed. Regression analysis revealed that the mean increase in CH_4 content in most of the studied regions/countries was about 15 ppb per year. CH_4 content evaluated with the use of satellite data from Sentinel-5P is a reliable data source and can be used for the analysis of temporal changes at various spatial scales, including regions and countries.

Keywords: Sentinel-5P; GHG emissions; China; India; Bangladesh; Thailand; USA

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1. Introduction

Rice is one of the most important crops in the world with a cultivation area covering around 150 million hectares, of which around 50% is irrigated and flooded for most of the rice-growing season [1]. In the last 50 years, the global rice harvest area has increased by 40% due to the expansion and intensification of rice cultivation which is one of the staple foods for a rapidly growing population [2]. The rice-growing area is mainly located in Southeast Asia, which accounts for 90% of the world's rice cultivation [3,4]. In addition to China, India, and Thailand, the largest rice exporters are also the United States, where the cultivation is mainly located in the Arkansas Non-Delta, Mississippi River Delta, Gulf Coast, and Sacramento Valley of California regions [5]. The cultivation of rice is associated with increased methane (CH_4) emissions. The practice of flooding rice fields, leading to anaerobic conditions, promotes the formation and release of CH_4 [6]. The water blocks oxygen from penetrating the soil, creating ideal conditions for bacteria that emit CH_4.

CH_4 is the second most important anthropogenic greenhouse gas in the atmosphere, next to carbon dioxide (CO_2). Its global warming potential (GWP) over a 100-year time horizon is 25 times greater than that of CO_2 [7]. Global CH_4 emissions from rice fields are estimated to be more than 8% of total global anthropogenic CH_4 emissions [8]. Therefore, rice fields have a significant impact on the total global CH_4 emissions. Understanding the spatial distribution of CH_4 emissions from this crop and its changes over time is extremely important for understanding CH_4 emissions dynamics and for mitigating climate change.

Frequent mapping of CH_4 content at the global scale is possible using satellite sensors [9]. One of the most important sensors for such purpose, because of high spatial resolution and short revisit time, is the TROPOMI (TROPOspheric Monitoring Instrument). It is placed on the Sentinel-5 Precursor (Sentinel-5P) satellite board, which was launched in October 2017 [10]. Satellite data from Sentinel-5P can be transformed to the column-averaged dry-air mixing ratio of CH_4 in the atmosphere at spatial resolution 7×7 (to August 2019) and 7×5.5 km (from August 2019) [11]. For evaluation of CH_4 content, two spectral ranges are used, i.e., near-infrared (NIR): 675–775 and short-wave infrared (SWIR): 2305–2385 nm [12]. CH_4 content based on Sentinel-5P data is available so far only for land surfaces. For water surfaces, it will be available in a later phase. Satellite CH_4 content measurements can be treated as reliable data [13,14]. Sentinel-5P-derived CH_4 content is in good agreement with ground-based measurements from the Total Carbon Column Observing Network (TCCON), as well as with data derived from GOSAT satellite observations. TCCON and GOSAT satellite observations have been considered a source of reliable data used for the evaluation of methane content in the atmosphere for many years. Sentinel-5P is quite a new source of such data but high agreement with these two data sources allows considering these data as reliable for evaluation CH_4 content all over the globe. In most cases, the standard deviation of mean bias between Sentinel-5P derived CH_4 and TCCON is not greater than 15 ppb [15]. When comparing the CH_4 content obtained from Sentinel 5P vs. GOSAT, the mean difference was 13.6 ppb, the standard deviation was 19.6 ppb, and the Pearson correlation coefficient was 0.95 [16]. The relative difference between Sentinel-5P versus TCCON-derived methane is very small, less than 1% and a very high correlation coefficient confirms a very high agreement between these two sources of data.

The aim of the study was to evaluate the spatial-temporal changes in CH_4 content in the atmosphere for selected countries and regions with high CH_4 emissions from rice cultivation in 2019–2021. Using Sentinel-5T data, it can be proven that the CH_4 content in the atmosphere is characterized by long-lasting growth and seasonal variability.

2. Materials and Methods

2.1. Study Area

Several countries and regions within countries were selected for the study. In the first step of the analysis, countries were selected based on the high share of CH_4 emissions from rice cultivation among agricultural sources using the latest FAOSTAT data for 2019 [17]. The following countries were selected (from the lowest—18% to the highest share—78%): Nepal, Cote d'Ivoire, Solomon Islands, Iraq, Suriname, Dominican Republic, India, Guyana, Lao People's Democratic Republic, Madagascar, French Guyana, Nigeria, Indonesia, Egypt, Guinea, Myanmar, China, South Korea, Sierra Leone, Gambia, Malaysia, Bangladesh, Japan, North Korea, Cambodia, Sri Lanka, Vietnam, Comoros, Thailand, Philippines. Then, those with at least 10% of the rice cultivation area of the total region/country area were selected. We also added the part of the area of the United States because, although it does not have a high share of rice emissions in the total CH_4 emissions. The area taken up by rice crops in the Mississippi region is above 10%. The high spatial resolution (five minutes spatial resolution~10 km $\times$ 10 km) data about rice crop share in the total land area come from the study of Ramankutty et al. [18] available at EarthStat/ [19]. They were used for the calculation of rice crop share for selected regions to evaluate the rice share by region/country.

Figure 1 presents a map with the countries and regions included in the study.

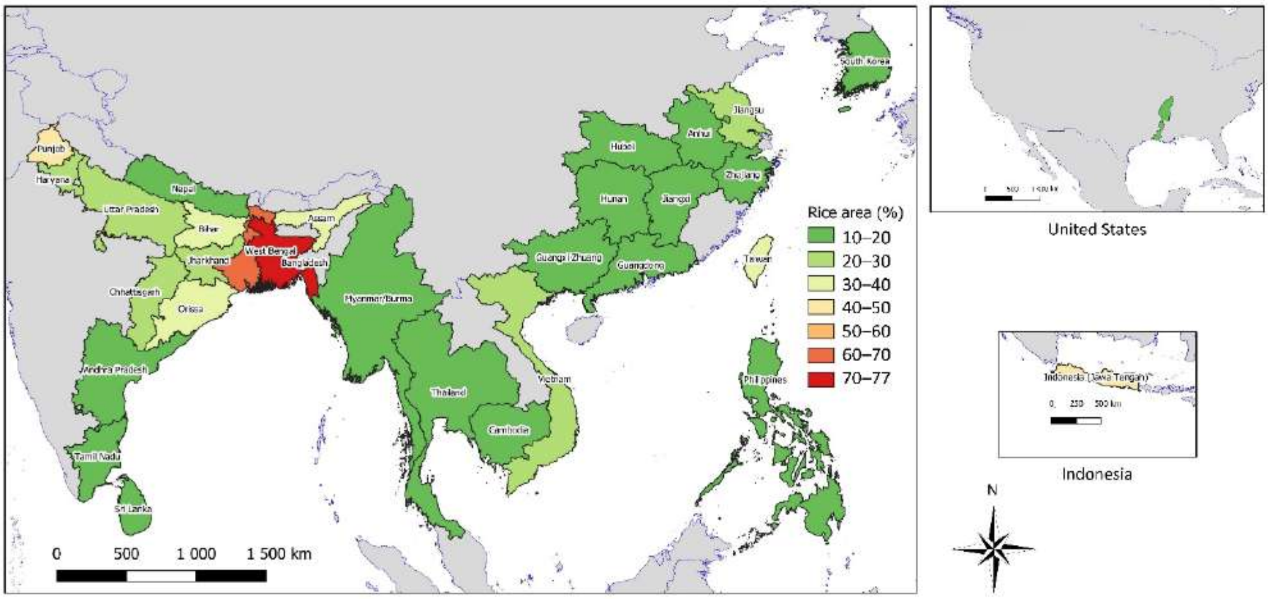

Figure 1. Countries and regions included in the study with percentage of rice area (as percent of total land, own graphics based on the data from http://www.earthstat.org/ (accessed on 5 July 2021)).

2.2. Satellite Data

Data from Sentinel-5P were used for the analyzes. The column-averaged dry-air mixing ratio of CH_4 (in ppb—parts per billion) data for the period from 8 February 2019 to 30 June 2021 were used. The Sentinel-5P imagery from the TROPOMI sensor processed as Level 3 (L3) product was used [20]. Datasets were downloaded from the image collection "COPERNICUS/S5P/OFFL/L3_CH4" of Google Earth Engine as georeferenced raster files (in GeoTIFF format file) at spatial resolution 7 × 7 km. Mean values of the column-averaged dry-air mixing ratio of CH_4 for 3-month periods were analyzed. The only exception was the first period, which was shorter (from 8 February–31 March 2019).

2.3. Data Analysis

Raster files (GeoTIFF) containing averaged values of the air-methane mixing coefficient were used for further processing. For selected countries or regions, the mean CH_4 content for each study period was calculated using the zonal statistics tool in QGIS 3.18 software [21]. The means were used for evaluating the seasonal (within years) and between years changes. Moreover, within countries/regions, spatial-temporal variability was evaluated based on maps for each country or region. The results for the studied countries/regions were compared to the reference areas, i.e., neighboring areas without high concentration of rice cultivation. Three areas were selected as references, i.e., India (without the states with high rice concentration), China (without the provinces with high rice concentration), and the United States (excluding region with high rice concentration).

Relationship between estimated GHG emissions from croplands [19,22] and the mean content of CH_4 for the total period of study (from 8 February 2019 to 30 June 2021) were evaluated using Pearson's correlation coefficient and for selected countries/regions using linear regression analysis.

The worldwide geographical layer of GHG emissions from croplands used for the analyses is at five minutes spatial resolution (~10 km × 10 km) and is based on circa 2000 estimates of GHG emissions which are presented in CO_2 equivalent and include CH_4, CO_2, and N_2O emissions. In the case of regions with a high concentration of rice paddy, the emission is mainly determined by CH_4 emissions from that crop and their percentage is quite stable from 2000 until now [17]. More details about the methods used for the estimation of GHG emissions are available in the study of Carlson et al. [22] and available at EarthStat [19].

The relationships were evaluated separately for each country/region. These analyses were performed at 42-arc minutes (0.7 degrees of longitude and latitude) resolution, i.e., unit areas of about 75 × 75 km (~5600 km^2). For each square, the average CH_4 content and the average estimated GHG emissions were calculated in QGIS using zonal statistics. Then, the correlations were calculated separately for each country/region in the Statistica program [23]. The operation was repeated four times with different grid shifts: offset 0, 0.35, 0.175, and 0.525. Then the average, min, and max correlation coefficients were calculated.

Only areas inside the countries/regions were included in the analyses. Units that were located next to the borders of the countries/regions were removed (criterion was at least 3500 km^2 of area located inside the country or region). Because of the various sizes of the countries/regions, the number of observations (n) for the analyses varied from 5 to 112. Small regions of rice cultivation were removed from these analyses because the sample size was too small. Due to various sample sizes, the significance of the relationships strongly depends on the number of observations and varies between the countries/regions.

3. Results

3.1. Methane Content by Country/Region

The mean content of CH_4 for the total period of the study (from 8 February 2019 to 30 June 2021) was quite similar for all the studied counties (Table 1).

The lowest content of CH_4 (1836 ppb) was observed for Jawa Tengah (an island which is part of Indonesia) while the highest (1904 ppb) for Jiangsu (province of China). These differences between the mean CH_4 content for the countries/regions were caused rather by worldwide CH_4 spatial variability not local emissions from rice fields. Because of that, further analyses were performed separately for each country/region to avoid the effect of worldwide CH_4 variability. Visual evaluation of the spatial variability on CH_4 content for the total period of the study based on maps presented in Figure 2 indicates higher CH_4 content for areas with high rice concentration. One of the most visible cases is the region of rice cultivation located along the Mississippi River (United States) where CH_4 content is much higher (about 50 ppb higher) in comparison to neighboring areas. However, such high CH_4 content in areas of rice concentration does not always occur.

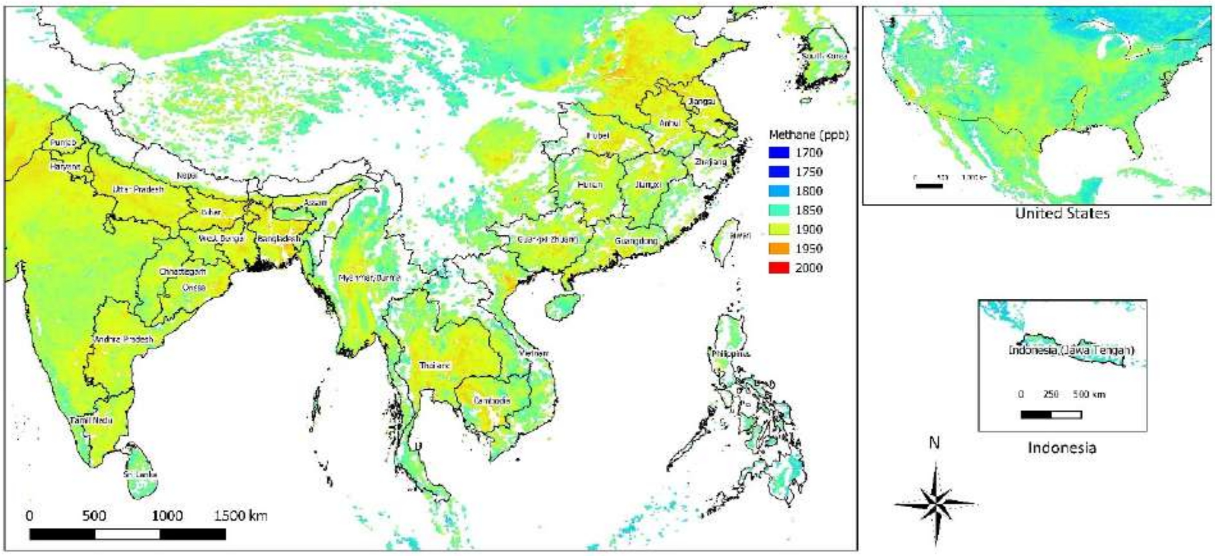

Figure 2. Mean CH_4 content for the studied period (from 8 February 2019 to 30 June 2021) based on Google Earth Engine https://earthengine.google.com/ (accessed on 5 July 2021).

Table 1. Mean CH_4 content for total period of the study (from 8 February 2019 to 30 June 2021) for studied countries/regions, estimated emissions of GHG from croplands, and correlations between CH_4 content and estimated GHG emissions by region/country. Calculated using the data from: http://www.earthstat.org/greenhouse-gas-emissions-croplands/ (accessed on 5 July 2021) and Google Earth Engine https://earthengine.google.com/ (accessed on 5 July 2021) [19].

Country/Region	Country	CH_4 Content in Atmosphere (ppb)	Estimated GHG Emissions from Croplands (Mg CO_2e Per Hectare) *	Mean Correlation	Min. Correlation	Max. Correlation
Zhejiang	China	1886	4.12	0.28	0.16	0.43
Jiangxi	China	1887	3.84	0.02	−0.03	0.06
Hubei	China	1892	3.09	0.79	0.77	0.81
Anhui	China	1897	3.26	−0.38	−0.47	−0.25
Jiangsu	China	1904	3.25	−0.49	−0.53	−0.41
Hunan	China	1886	4.04	0.62	0.57	0.68
Guangxi Zhuang	China	1889	3.16	0.27	0.20	0.36
Taiwan	China	1878	2.16	0.43	−0.20	0.76
Guangdong	China	1889	3.58	−0.54	−0.61	−0.48
Andhra Pradesh	India	1894	2.09	−0.30	−0.40	−0.21
Assam	India	1893	2.04	0.25	0.13	0.39
Bihar	India	1903	3.16	−0.53	−0.76	−0.41
Chhattisgarh	India	1889	2.53	0.37	0.18	0.68
Haryana	India	1898	2.42	−0.66	−0.82	−0.53
Jharkhand	India	1895	1.65	0.17	0.06	0.23
Orissa	India	1893	2.74	0.35	0.28	0.44
Punjab	India	1895	4.21	0.48	0.24	0.77
Tamil Nadu	India	1893	2.00	−0.11	−0.37	0.17
Uttar Pradesh	India	1901	2.15	−0.20	−0.25	−0.11
West Bengal	India	1901	3.79	0.42	0.34	0.52
Jawa Tengah (Indonesia)		1836	8.77	0.14	0.08	0.17
Mississippi region (USA)		1884	1.69	0.36	−0.02	0.68
Bangladesh		1903	3.56	−0.27	−0.44	−0.10
Sri Lanka		1863	5.41	0.25	−0.15	0.70
Cambodia		1889	2.47	0.52	0.45	0.60
South Korea		1872	6.40	−0.06	−0.22	0.16
Myanmar/Burma		1877	1.16	0.37	0.35	0.38
Nepal		1890	1.73	0.63	0.22	0.85
Philippines		1853	1.76	0.59	0.04	0.78
Thailand		1889	3.40	0.42	0.16	0.53
Vietnam		1877	7.51	0.24	0.18	0.31

* Significant correlations at 0.05 probability level are in red font. Because of various sample sizes (N) significance of the relationships strongly depends on N used for the analyses and varies between the countries/regions. For countries/regions with larger N critical value of correlation coefficient is lower in comparison to countries/regions where N was lower. Green color indicates low content of CH_4 in atmosphere (ppb) and estimated GHG emissions from croplands, while red color indicates high values of these variables. Blue color indicates low values of correlation coefficient (negative correlations), while red color indicates high values (positive correlations).

3.2. Temporal Changes in CH_4 Content

During the period of the study, seasonal changes, as well as a long-term trend, was observed for the content of CH_4 in most of the countries (Table 2). All provinces of China were characterized by a very similar pattern of changes in time. Seasonal changes of CH_4 were characterized by the lowest content at the beginning of the year (for the first quarter of the year) and the highest for the third quarter of the year. Moreover, a long-term increase in CH_4 was observed. On average, in the period of the study, an increase in CH_4 content by 15 ppb per year was observed for the studied provinces of China. Similar seasonal and long-term changes were observed for other regions and countries in Southeast Asia but in some cases, the changes were quite different. For example, in the states Tamil Nadu and Andhra Pradesh (Southeast India), the lowest seasonal CH_4 content was observed for the third quarter of the year. Another example of the exception is Jawa Tengah island (Indonesia), where seasonal changes for CH_4 content were very small but long-term changes were very similar to those observed for China. In the Mississippi region (USA), the highest seasonal CH_4 content was observed at the end of the year (the fourth quarter of the year), while the lowest was at the beginning of the year. Long-term changes for CH_4 were similar for most of the regions of Southeast Asia (increase of about 16 ppb per year). Regression equations presented in Figure 3, which presents averaged CH_4 content for 3-month periods, confirm that the mean increase in CH_4 content in regions/countries of Southeast Asia is about 16 ppb per year (about 4 ppb per each 3-month period), while in the Mississippi region (United States) the mean increase was about 15.5 ppb per year (3.87 ppb per 3-month period). A similar long-term increase was observed for both parts of India, i.e., where high concentrations of rice production occur, and for other areas of India (mean increase in CH_4 content by about 16 ppb per year). In the case of the United States reference area, which is most of the area of the US excluding the main regions of rice cultivation, the mean yearly increase in CH_4 content was smaller in comparison to regions with high rice concentration (respectively 13.56 ppb vs. 15.48 ppb of CH_4). The increase for total world area (limited to latitudes between 60° S and 60° N) is 12.8 ppb per year (3.20 ppb per 3-month period) and is lower in comparison to areas with rice cultivation. Similar results but for 1-month periods are presented in Figure S1 and allow evaluating temporal changes of CH_4 content at higher temporal resolution. It allows observing the short time increase in late summer and beginning of autumn in CH_4 content in the regions/countries in south-eastern Asia. The most visible increase can be noticed in Bangladesh in October when maximal CH_4 content was observed. The temporal changes observed for 1-month periods are much lower for reference areas, i.e., for total of the United States and total world, which suggest that are strongly dependent on the rice growing period. Regression equations based on 1-month periods presented in Figure S1 suggest a similar long-term trend of CH_4 but slightly different in comparison to the regression equations based on 3-month periods. For example, the mean yearly increase in CH_4 for total world area (limited to latitudes between 60° S and 60° N) based on regression equation for 1-month periods was equal to 14.1 ppb while based on 3-month periods was slightly lower and equal to 12.9 ppb. Usually, regression equations for studied regions/countries based on 1-month periods prove a slightly higher increase in CH_4 in comparison to an increase in CH_4 based on respective regression equations for 3-month periods. This is probably caused by higher peaks (yearly maximal content of CH_4) for 1-month periods in comparison to 3-month periods.

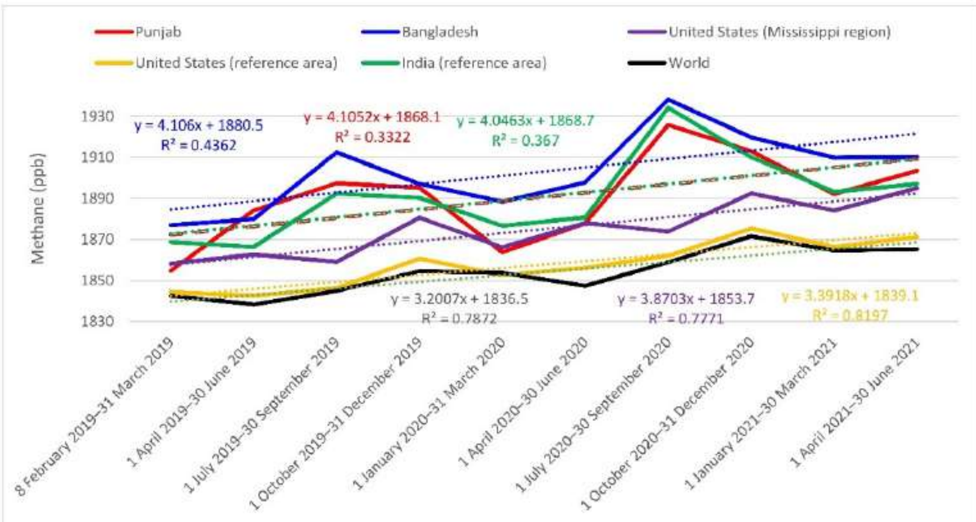

Figure 3. Temporal changes in selected countries/regions and total world (limited to latitudes between 60° S and 60° N) of CH_4 content based on Sentinel-5P data (in ppb) and regression equation presenting relationships between CH_4 content (y) and subsequent 3-month periods (x).

Table 2. Means of CH_4 content for selected countries or regions based on Sentinel-5P data (in ppb) and regression equation presenting relationships between CH_4 content (y) and subsequent 3-month periods (x).

Country/Region	Country	8 February–31 March 2019	1 April–30 June 2019	1 July–30 September 2019	1 October–31 December 2019	1 January–31 March 2020	1 April–30 June 2020	1 July–30 September 2020	1 October–31 December 2020	1 January–31 March 2021	1 April–30 June 2021	Linear Regression
Zhejiang	China	1862	1871	1900	1888	1865	1877	1904	1898	1882	1901	y = 2.9·x + 1868.9
Jiangxi	China	1864	1879	1901	1879	1865	1886	1909	1900	1882	1907	y = 3.1·x + 1870.0
Hubei	China	1863	1881	1910	1885	1871	1890	1915	1907	1886	1907	y = 3.2·x + 1873.9
Anhui	China	1868	1879	1904	1891	1873	1887	1926	1912	1889	1907	y = 3.5·x + 1874.3
Jiangsu	China	1870	1877	1906	1896	1876	1883	1926	1913	1893	1911	y = 3.7·x + 1874.7
Hunan	China	1859	1868	1904	1881	1862	1883	1900	1905	1883	1902	y = 3.5·x + 1865.3
Guangxi Zhuang	China	1857	1845	1909	1881	1861	1876	1901	1903	1882	1895	y = 3.9·x + 1859.7
Taiwan	China	1856	1848	1890	1874	1859		1944	1887	1889	1885	y = 4.7·x + 1855.8
Guangdong	China	1865	1845	1907	1880	1864	1875	1925	1898	1886	1891	y = 3.7·x + 1862.9
Andhra Pradesh	India	1876	1870	1859	1907	1882	1887	1884	1919	1900	1904	y = 4.3·x + 1865.4
Assam	India	1877	1878	1904	1880	1879	1889	1912	1899	1897	1904	y = 2.7·x + 1877.0
Bihar	India	1867	1887	1893	1898	1879	1888	1964	1933	1907	1909	y = 5.6·x + 1871.8
Chhattisgarh	India	1867	1867	1843	1886	1873	1878	1912	1907	1891	1896	y = 5.0·x + 1854.3
Haryana	India	1851	1888	1895	1893	1866	1884	1933	1920	1889	1903	y = 4.4·x + 1867.8
Jharkhand	India	1869	1873	1888	1890	1879	1881		1918	1899	1903	y = 4.0·x + 1868.0
Orissa	India	1870	1866	1853	1891	1878	1877	1928	1913	1898	1899	y = 5.4·x + 1857.9
Punjab	India	1855	1884	1897	1895	1864	1878	1926	1913	1892	1903	y = 4.1·x + 1868.1
Tamil Nadu	India	1872	1872	1845	1919	1881	1888	1857	1910	1903	1891	y = 3.3·x + 1865.9
Uttar Pradesh	India	1863	1885	1904	1895	1875	1887	1941	1928	1897	1904	y = 4.4·x + 1873.4
West Bengal	India	1875	1872	1913	1897	1885	1885	1947	1925	1909	1906	y = 4.5·x + 1876.8
Jawa Tengah (Indonesia)		1817	1825	1831	1838	1833	1834	1845	1840	1859	1850	y = 3.6·x + 1817.2
Mississippi region (USA)		1858	1863	1859	1881	1866	1878	1874	1892	1884	1895	y = 3.9·x + 1853.7
Bangladesh		1877	1880	1912	1897	1888	1898	1938	1920	1910	1910	y = 4.1·x + 1880.5
Sri Lanka		1851	1835	1819	1874	1864	1849	1836	1877	1877	1869	y = 3.7·x + 1834.6
Cambodia		1863	1849	1866	1878	1873	1861	1853	1891	1894	1879	y = 3.0·x + 1854.3
South Korea		1849	1854	1876	1865	1854	1864	1875	1885	1873	1883	y = 3.2·x + 1850.0
Myanmar/Burma		1860	1867	1888	1871	1869	1880	1916	1890	1881	1892	y = 3.3·x + 1863.5
Nepal		1856	1872	1885	1879	1863	1876	1976	1904	1894	1898	y = 5.6·x + 1859.2
Philippines		1848	1846	1834	1859	1860	1856	1846	1871	1872	1878	y = 3.5·x + 1837.5
Thailand		1865	1862	1918	1885	1880	1882	1874	1898	1895	1882	y = 1.5·x + 1875.7
Vietnam		1851	1854	1901	1879	1864	1867	1898	1901	1882	1878	y = 3.1·x + 1860.6
India (reference area)		1869	1866	1892	1890	1877	1881	1934	1910	1893	1897	y = 4.0·x + 1868.7
China (reference area)		1838	1850	1871	1871	1860	1860	1884	1884	1868	1879	y = 3.6·x + 1846.5
United States (reference area)		1844	1843	1846	1861	1853	1856	1862	1875	1866	1871	y = 3.4·x + 1839.1

Blue color indicates low values while red color indicates high values of CH_4 content.

3.3. Spatial-Temporal Variability in CH_4 Content for Selected Countries/Regions

Three countries/regions were selected for a more detailed evaluation of spatial-temporal changes in CH_4 content during the period of the study. Figures 4–6 present spatial-temporal variability by 3-month periods while Figures S2–S4 present maps based on a 1-month period. These countries/regions were selected based on various criteria. The first region is Bangladesh, which is characterized by a very high percentage of rice cultivation area—about 70% of the total country area. Therefore, CH_4 emissions from rice fields are very high. However, the highest content of CH_4 was observed for the area of the capital city—Dhaka (Figures 4, 7 and S2). Because of the limited availability of data for the third quarter of the year, in years 2019 and 2020, CH_4 content for this period can be biased, especially for the results based on 1-month periods. The reason for very limited availability is the monsoon period (from July to September) which is characterized by overcast conditions. The highest CH_4 content was observed for the third quarter of the year, especially for October, i.e., for the end of the rice period called "aman", when most of the rice in Bangladesh is harvested. In most of Bangladesh's area, the share of rice cultivation area is very high, the exceptions are two regions located next to the coast, i.e., the southwest part where mangrove forests are located and the southeast part with hill forests. In both of these areas, CH_4 content is lower in comparison to the CH_4 content in other areas of Bangladesh.

Figure 5, 7 and S3 present CH_4 content in the main area of rice cultivation in the United States located along the Mississippi River in the mouth of the river and in the lower course of the river (next to the border of Mississippi State with Arkansas and Louisiana). The area of the rice cultivation is interesting because in neighboring areas there is no rice and the effect of the rice cultivation on CH_4 content in the atmosphere can be better evaluated. The CH_4 content in the atmosphere, in the area of rice cultivation, is higher in comparison to the nearest surrounding area. The differences are most visible during the fourth quarter of the year (September–December) which is the harvest time of the rice, with the maximum value of CH_4 in October and November. In other seasons of the year, the differences are visible, but the smallest is observed during the first quarter of the year (January–March).

Spatial-temporal changes of CH_4 content in Punjab state (India) are presented in Figures 6, 7 and S4. The highest CH_4 content was observed in the third quarter of the year (in the middle of the growing period of rice) with maximum value in September, while the lowest in the first quarter of the year with minimal value in February–March. The lowest CH_4 content was observed in the Northeast part of Punjab where the share of the rice area is smaller in comparison to other parts of the Punjab state.

3.4. Relationships between Estimated GHG Emissions and CH_4 Content

Correlations between estimated GHG emissions and methane content are presented in Table 1. Most of the correlations are positive, as expected. Some of the correlations are negative but relatively weak. The correlations were calculated separately for each country/region at 42-arc minutes (0.7 degrees) spatial resolution. The strongest positive correlations were observed for Hubei and Hunan (provinces of China), Punjab (state of India), Cambodia, Philippines, and Nepal. Mean correlation coefficients for these regions/countries were between 0.48 and 0.79. For some countries/regions, the correlations were negative.

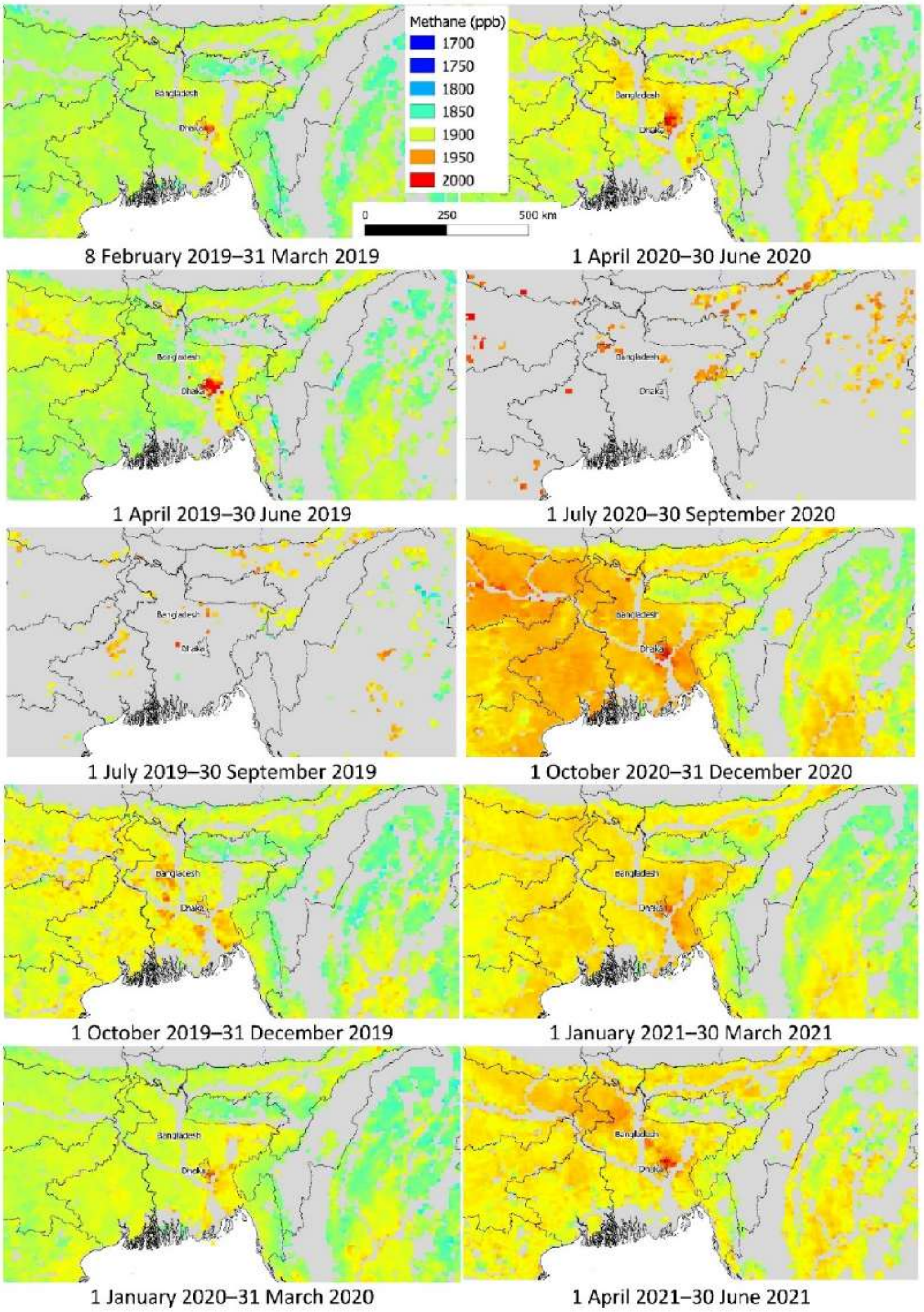

Figure 4. CH_4 content in Bangladesh in subsequent 3-month periods. Maps were prepared using data from https://earthengine.google.com/ (accessed on 5 July 2021).

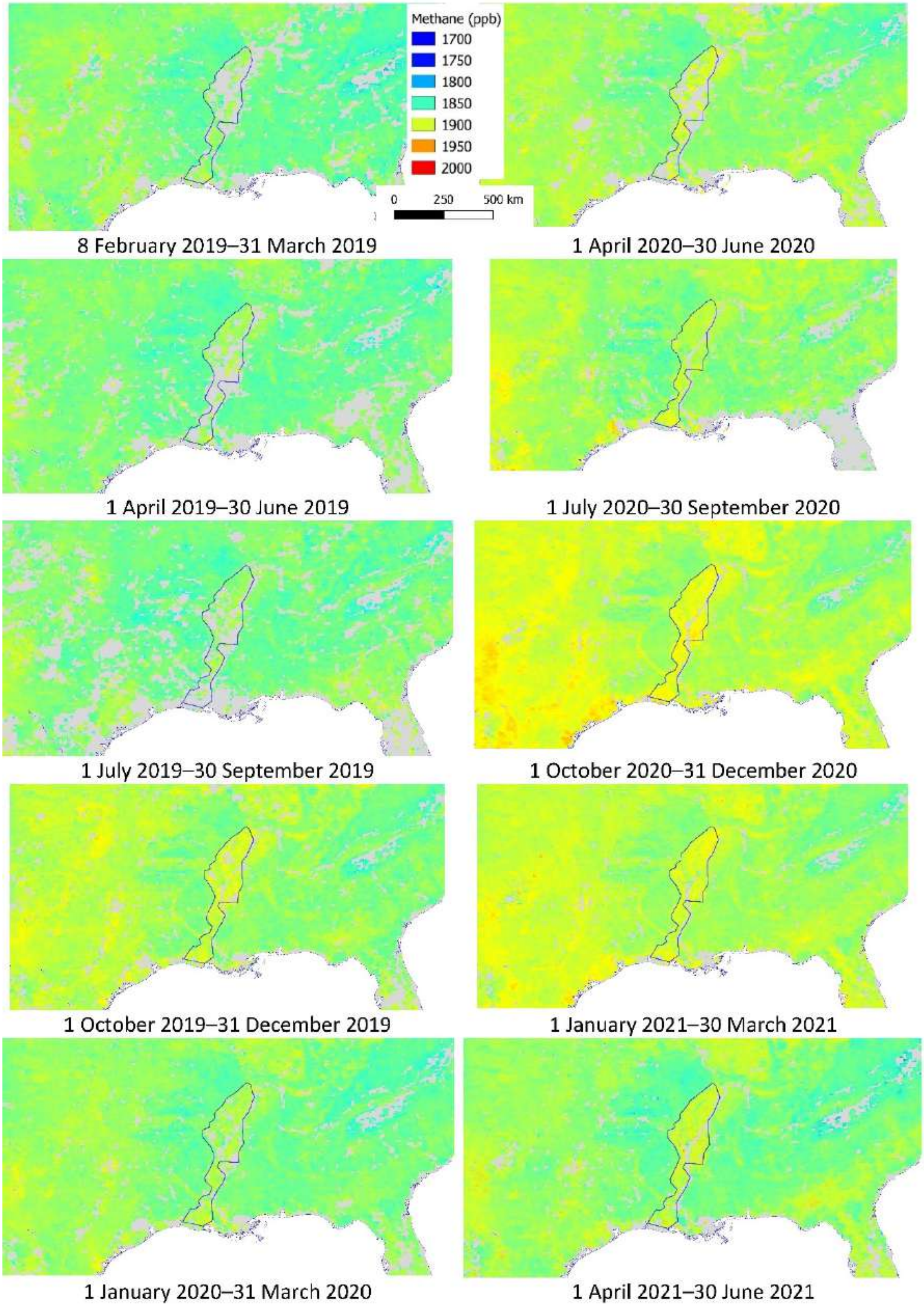

Figure 5. CH_4 content in Mississippi Valley (United States) in subsequent 3-month periods. Maps were prepared using data from https://earthengine.google.com/ (accessed on 5 July 2021).

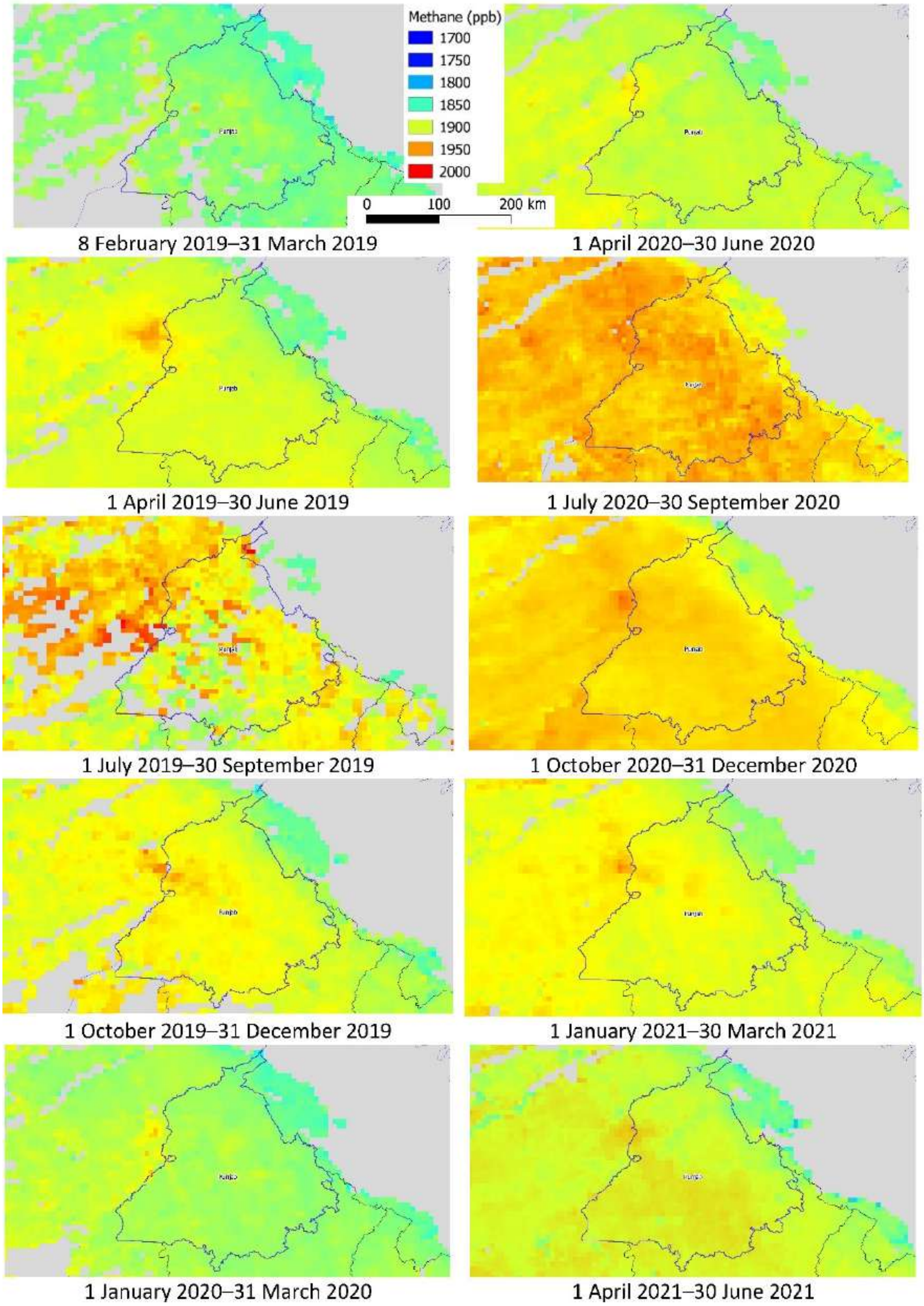

Figure 6. CH_4 content in Punjab state (India) in subsequent 3-month periods. Maps were prepared using data from https://earthengine.google.com/ (accessed on 5 July 2021).

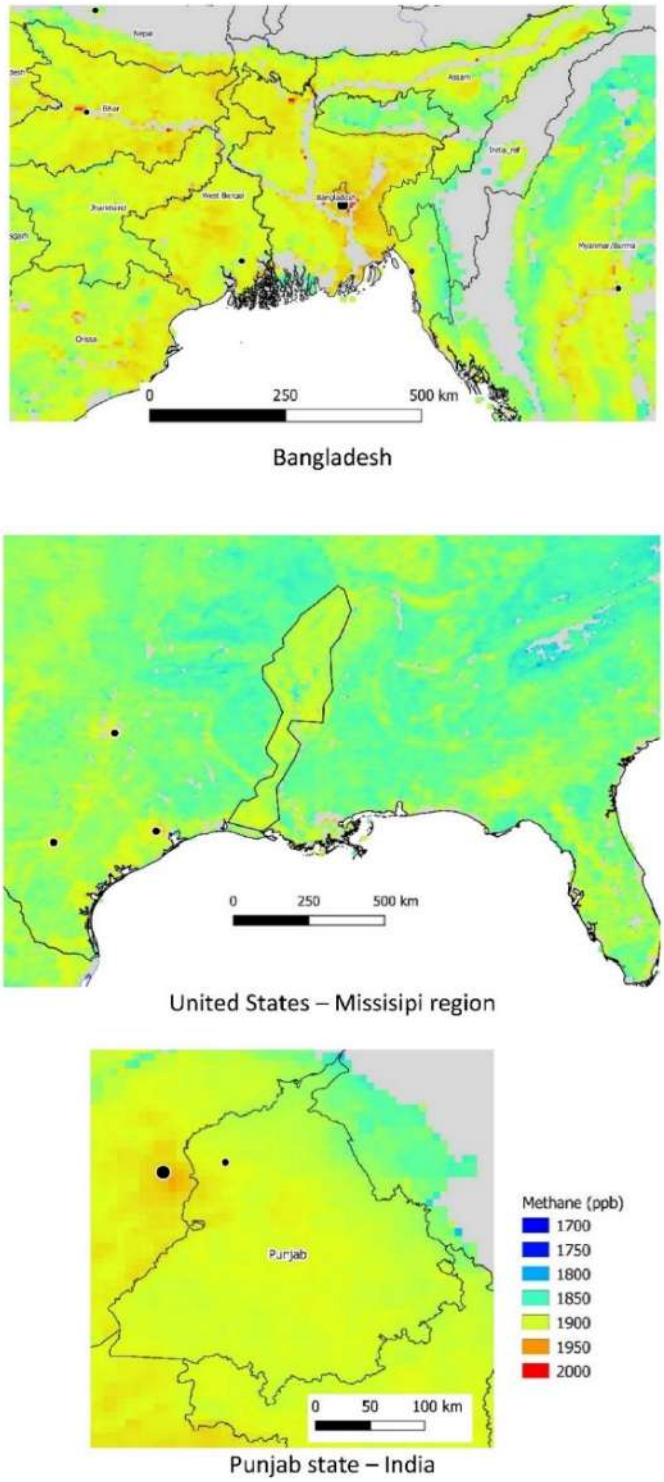

Figure 7. Mean CH_4 content in selected regions (Bangladesh, the United States, and Punjab state—India for all periods of the study—8 February 2019–30 June 2021). Big black dots indicate the largest cities (with population 5 million or greater) and small black dots indicate big cities (with population in range 1–5 million).

4. Discussion

The results obtained in this study proved a long-term increase in methane content in studied countries/regions. The mean increase for most of the countries/regions with high rice concentration was about 16 ppb of CH_4 per year. Rice is the most important crop in wetlands and pressure to grow rice is increasing. Rice is the only major cereal crop that is grown almost exclusively as food. In view of the growing number of people on earth, world rice production will continue to increase. The results are consistent with CH_4 content from corresponding data from Total Carbon Column Observing Network (TCCON) locations [13]. It confirms that CH_4 content evaluated on the basis of satellite data from Sentinel-5P is a reliable data source and can be used for the analysis of temporal changes at various spatial scales, including regions and countries.

The increase in CH_4 content during the study period is much higher in comparison to previous years which was at a global scale in average in the range from about 0 to about 12 ppb per year in various periods from the 1980s [24,25]. The results of the study of [26] based on in situ measurements, for years 2014–2017, proved a mean yearly global increase in CH_4 from 7.0 to 12.7 ppb. A strong global increase in CH_4 content in the atmosphere is observed from 2007 and in years 2007–2017 was estimated at about 7 ppb per year. In recent years, the increase is even higher which is very worrying as it can significantly increase the greenhouse effect. In the study of Dalsøren et al. [26], long-term changes of CH_4 content during the period 1970–2012 are presented. The study proved quite a high increase in CH_4 content in the years 1986–1998, which was about 11 ppb per year. It indicates that the increase in CH_4 content is not uniform in longer periods and during the years 1970–2012, long periods with a different increase in CH_4 were observed.

Seasonal variability of CH_4 content in the study of Nisbet et al. [27]—observed at a global scale—was similar to seasonal variability in this study. The lowest CH_4 content was observed at the beginning of the year while the highest was observed in the middle of the year or in autumn. However, the seasonal (within year) amplitude for the countries/regions located in Southeast Asia with high rice concentration was usually higher (50–60 ppb) in comparison to amplitude observed at a global scale (about 40 ppb). A smaller seasonal amplitude of atmospheric CH_4 content was observed for the United States where it was equal to about 20 ppb. There are many factors that influence the seasonal variability of CH_4 emissions. Firstly, the presence of rice plants enhances the escape of methane from the soil. The main factors controlling the level of CH_4 emission during the growing season are positively related to the water level and plant cover. The main controlling factors during the set-aside period are the water level, as well as straw absorption and soil temperature.

The amplitudes observed in Southeast Asia in this study were higher in comparison to the results of Crevoisier et al. [28] for years 2007–2011 where seasonal variations were from about 15 ppb to about 40 ppb depending on the region (higher were observed for Northern Hemisphere than in Southern Hemisphere). Higher seasonal amplitudes of CH_4 content in regions of Southeast Asia can be connected with the growing cycle of rice because other anthropological sources of CH_4 emissions (e.g., landfills) are more stable in time and are not characterized by high seasonal changes. The most important rice-growing season in Bangladesh is called aman, which starts in April and ends in November or December [29]. In other countries of Southeast Asia, the most important rice vegetation period falls into a similar period, i.e., starts in spring and ends in autumn [30,31]. The highest CH_4 content is observed during the intensive growth of rice during aman period. A study by Adhya et al. [30] conducted in Indian conditions proved the highest CH_4 emission from rice crop about 2–2.5 months after rice germination or transplantation. Depending on the rice crop calendar, such high emissions are observed in various months but are most often in the monsoon season, i.e., between June and September. The highest CH_4 content in the atmosphere in East China falls into the third quarter of the year which is the period of the highest CH_4 fluxes from rice paddies [31]. Seasonal compliance of the increases in CH_4 content with the rice crop vegetation was also found in the studies of Zhang et al. [4] for various regions of India, China, and Bangladesh, i.e., the highest CH_4 content was observed during the most intensive growth of the rice.

Effect of rice cultivation on seasonal variation of CH_4 content in the atmosphere is confirmed by observation of the CH_4 content in regions where rice is not cultivated. Examples of such areas are South-Western and South-Eastern parts of Bangladesh where forests are located [32]. In these areas, CH_4 content is not only lower but seasonal variation of CH_4 is much lower in comparison to other parts of Bangladesh where rice is cultivated. A similar pattern of seasonal changes of CH_4 content is observed in the Mississippi region, where higher CH_4 content and higher seasonal amplitudes are observed for areas with rice cultivation in comparison to neighboring areas where rice is not cultivated.

Most of the correlations evaluated in this study between estimated GHG emissions and CH_4 content were positively correlated, which is consistent with expectations. Positive relationships between atmospheric CH_4 concentration with the percentage of paddy rice croplands were observed in the study of Zhang et al. [4] for Southeast Asia which confirms that methane emissions from rice fields are substantial and methane atmospheric transport in the horizontal direction is relatively slow. The CH_4 content in the study of Zhang et al. [4] was for the periods 2003–2005 and 2007–2009 from SCIAMACHY satellite sensor and for years 2011–2013 from TANSO-FTS satellite sensor. However, some of the correlations were negative. An explanation of negative correlations in the case of some countries/regions such as Bangladesh, Guangdong (province of China), and Bihar (state of India) could be higher CH_4 content near to locations of big cities where urban and industrial emissions of CH_4 occur [33], while rice crop concentration is rather low. Some negative correlations are difficult to explain, e.g., for Anhui and Jiangsu (provinces of China) and Haryana (state of India).

CH_4 from sources of emission, e.g., rice paddies are transported in the atmosphere mainly in the latitudinal direction because of prevailing winds [34]. It is caused by high atmospheric CH_4 content in areas where CH_4 emission is very low, e.g., in the Sahara Desert, where CH_4 is transported from Southeast Asia. Schuck et al. [35] confirm that methane can be transported from South Asia to North Africa. It is difficult to present direct evidence of the transport but similar methane content at the same latitude in Asia and Africa confirms such transport caused by trade winds. Seasonal variation of CH_4 over Asia suggests that CH_4 content in the atmosphere is strongly influenced by local surface emissions during summer. It confirms that despite long-distance atmospheric transport of CH_4, in large part it influences the content of CH_4 near sources of emission.

The results obtained in the study prove higher CH_4 content in the regions with high rice concentration in comparison to neighboring areas. However, it is difficult to distinguish precisely between CH_4 derived from rice crops and other CH_4 sources because of atmospheric transport of methane which is difficult to evaluate at high spatial and temporal resolution. However other sources of CH_4 (e.g., landfills) are characterized by much lower seasonal variability than CH_4 emissions from rice crops and this background CH_4 emission is quite stable in time [36,37]. Further studies on the detection of local CH_4 anomalies by combining satellite measurements with high-resolution forecasts [38] are necessary, together with higher temporal resolution of the corrected Sentinel 5-P imagery [39] to better evaluate CH_4 local and global transport and distinguish various sources of CH_4 emission.

5. Conclusions

CH_4 content in the atmosphere is characterized by long-term increases and seasonal variability. During the period of the study (2019–2021), the mean yearly increase in CH_4 was about 15 ppb for all the studied areas, however, large differences were observed between the countries/regions. The highest increase (about 20 ppb per year) was observed for the Southeast states of India, while the lowest increase was observed for countries located in the Southeast corner of Asia, i.e., Thailand (about 6 ppb per year), Vietnam, and Cambodia (about 12 ppb per year). For most of the other countries/regions, the mean increase in CH_4 was in the range from 13 to 18 ppb per year.

Seasonal changes of CH_4 content were characterized by the lowest CH_4 content at the beginning of the year while the highest content during autumn coincides in time with intensive growth of rice. It indicates that CH_4 emissions from paddy fields may have a significant effect on the seasonal variability of the CH_4 content in the atmosphere.

Relationships evaluated separately for each country/region proved in most cases positive correlations between CH_4 content in the atmosphere with estimated GHG emissions from croplands. This confirms that the CH_4 content is higher in areas with a high concentration of rice cultivation compared to neighboring areas. The main limitation of the study is the lack of possibility to distinguish precisely between emissions of CH_4 from paddy rice and other agricultural and non-agricultural sources of methane. Moreover, atmospheric transport of CH_4 is difficult to evaluate and affects the spatial variability of CH_4 content.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos12111382/s1, Figure S1: Temporal changes in selected countries/regions and total world (limited to latitudes between 60° S and 60° N) of CH_4 content based on Sentinel-5P data (in ppb) and regression equation presenting relationships between CH_4 content (y) and subsequent 1-month periods (x)., Figure S2: CH4 content in Bangladesh in subsequent 1-month periods, Figure S3: CH4 content in Mississippi valley (United States) in subsequent 1-month periods, Figure S4: CH4 content in Punjab state (India) in subsequent 1-month periods.

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**Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie**

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kozicka K., Gozdowski D., Wójcik-Gront E. 2021. Spatial-temporal changes of methane content in the atmosphere for selected countries and regions with high methane emission from rice cultivation. *Atmosphere* 12(11):1382, mój indywidualny udział w jej powstaniu polegał na opracowaniu założeń metodycznych, przetwarzaniu danych oraz przygotowaniu oryginalnego tekstu pracy. Udział procentowy szacuję na 55%.

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Evaluation of temporal changes in methane content in the atmosphere for areas with a very high rice concentration based on Sentinel-5P data

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ABSTRACT

Rice cultivation is one of the main sources of methane (CH_4) emission into the atmosphere. The research aimed to assess long–term and seasonal changes in CH_4 content in the atmosphere in areas where rice production exceeds 30% of the area. These areas include India, Bangladesh, Myanmar and Indonesia. CH_4 content was evaluated using the Sentinel–5P TROPOMI sensor on a monthly basis from February 2019 to January 2022. Long–term and seasonal changes were assessed using statistical methods such as regression analysis and time–series analysis. The results showed that the long-term trend indicates an increase in CH_4 concentration. In the analyzed period, the average annual increase in the CH_4 content in the atmosphere was highest in eastern India (Bihar and West Bengal areas) and Bangladesh, from 15.9 to 19.6 ppb per year, while in Myanmar (Ayeyarwady) and Indonesia (Java) it was much lower, 3.7 and 9.9 ppb, respectively. Seasonal variability in CH_4 content in the atmosphere was characterized by a large annual amplitude in the rice regions of India (from 47 to 58 ppb) and was consistent with CH_4 emissions during a typical rice growth cycle. The highest CH_4 content was observed in late summer i.e., before rice harvest. The results of the Sentinel–5P measurements confirm the spatial–temporal variability of atmospheric CH_4 content in regions with a high share of rice production.

1. Introduction

Rice is a major crop worldwide and plays a crucial role in ensuring global food security. According to the International Food Policy Research Institute, the demand for rice increases by 1.8% per year due to the growing population (Clauss et al., 2018; Xiao et al., 2021). Rice production is constantly increasing, with Southeast Asia accounting for around 90% of the world's rice production, particularly in China, India, and Bangladesh (Prasad et al., 2017). However, rice is also the crop with the highest greenhouse gas (GHG) intensity, compared to other major food crops (Carlson et al., 2017; Linquist et al., 2012). The primary contributor to this intensity are methane (CH_4) emissions. They account for 8% of the total anthropogenic CH_4 emissions (Global Methane Initiative, 2020). These emissions result from the practice of flooding fields, which creates anaerobic conditions ideal for archaea microorganisms, commonly known as methanogenic bacteria, whose respiration product is CH_4 (Ji et al., 2018; Sanchis et al., 2012). The organic matter, mainly rice plant straw, decomposes during the rainy season and flooding, as well as newly formed plant parts. CH_4 is mainly released into the atmosphere via rice aerenchyma, as well as through the diffusion of dissolved CH_4 through the water interface and bubble ebullition caused by soil fauna or mechanical soil cultivation (Le Mer and Roger, 2001; Neue et al., 1990; Nouchi et al., 1994).

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CH_4 is the second most important GHG, after carbon dioxide (CO_2), in terms of its contribution to global warming. Various studies estimate the contribution of CH_4 to global warming from several to about 25% (Ali et al., 2013; Badr et al., 1991; Qu et al., 2021). Agricultural-related CH_4 emissions account for approximately two-thirds of total anthropogenic emissions (Saunois et al., 2020). The main sources include emissions from animals (cows, sheep, and other ruminants), manure management, rice cultivation and waste. Due to global population growth and the resulting high demand for food, CH_4 emissions from the agricultural sector continue to rise (Jackson et al., 2021). Mean global CH_4 concentration in the atmosphere in January 2022 reached 1908.9 ppb and the annual increase in the last two years was near 1% i.e., 15.06 ppb and 18.34 ppb in 2020 and 2021, respectively (Lan et al., 2022). The increase in recent years was the highest in the last 40 years since the Global Monitoring Division of NOAA's Earth System Research Laboratory started measurements of CH_4 at a globally distributed network of air sampling sites.

Measurement of CH_4 concentration in the atmosphere on a global scale is possible using various methods, including the use of satellite sensors (Liu et al., 2021). One of the most important earth observation satellite dedicated to monitoring GHG emissions, including CH_4, is GOSAT (Greenhouse gases Observing SATellite), launched in 2009 and still operational. Another sensor enabling monitoring of CH_4 concentration on a global scale is SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY) which was part of the Envisat satellite and operated in 2002–2012. The most recent satellite sensor dedicated to CH_4 monitoring on a global scale is TROPOMI (TROPOspheric Monitoring Instrument) aboard the Sentinel-5P (Sentinel 5 Precursor) satellite, which measures CH_4 at a spatial resolution of 7 × 7 km (from October 2017 to August 2019) or 5.5 × 7 km (from in August 2019 until now) (Veefkind et al., 2012). The CH_4 retrieval algorithm is based on two spectra bands i.e., reflectance in the NIR (757–774 nm) and SWIR (2305–2385 nm) ranges (Hu et al., 2016). A comparison of atmospheric CH_4 content between TROPOMI and GOSAT observations confirms that TROPOMI's CH_4 content measurements are reliable and accurate (Chen et al., 2022). The high accuracy of CH_4 measurement with the TROPOMI sensor is confirmed by a strong correlation ($r = 0.75$) with the EM27/SUN ground-based spectrometers (Sagar et al., 2022). Due to high spatial and temporal resolution, the CH_4 content derived from TROPOMI is used to evaluate spatial-temporal variability at different geographical scales, including variability in regions of rice cultivation (Chen et al., 2022; Kozicka et al., 2021; Zhang et al., 2022). It allows the assessment of long-term and seasonal changes in CH_4 content in the atmosphere caused by rice cultivation.

The analysis of atmospheric CH_4 concentration data in the study areas based on the recent satellite data enables an assessment of the CH_4 emissions trend from rice cultivation. This evaluation is significant due to the ongoing climate change and can be another step towards monitoring and reducing CH_4 emissions into the atmosphere. Therefore, based on the latest Sentinel–5P TROPOMI satellite measurement data, the aim of the study was to evaluate the long–term and seasonal changes in atmospheric CH_4 content in 2019–2022 in areas where the share of rice exceeds 30% of the total area and compare it to changes in global scale. This allowed the actual methane emissions from rice cultivation to be separated from other sources, including waste from large cities. Until now, there has been limited research on changes in methane content in areas with a significant proportion of rice cultivation. However, with the current availability of satellite data, it is now possible to examine such methane changes in greater detail by focusing on selected regions. The use of satellite remote sensing to analyze GHG emissions is a state-of-the-art technique for evaluating methane emissions based on their spatial and temporal distribution. With the aid of high spatial resolution satellite data from Sentinel-5P, with a pixel size of 7 km, it is now feasible to monitor frequent changes over time in specifically targeted areas.

2. Materials and methods

2.1. Study area

The first step of the study was the selection of areas with a high concentration of rice and references areas (without intensive rice cultivation). Table 1 shows the share of rice cultivation in total area with the information about rice harvested area, production and

Table 1
Percentage share of rice cultivation in total area, rice harvested area, production and yield in the studied areas. Based on the data from EarthStat (accessed on February 22).

Region	Country	% of total area	Harvested area (1000 ha)	Production (1000 tons)	Yield (tons ha^{-1})
Punjab	India	52.6%	3,874.40	20,136.11	5.04
Bihar	India	45.1%	3,364.20	8,565.87	2.49
Chhattisgargh	India	39.8%	3,135.53	6,148.39	1.94
West Bengal	India	67.8%	5,283.41	16,418.42	2.96
Bangladesh	Bangladesh	90.9%	6,711.63	22,324.62	3.33
Ayeyarwady	Myanmar	62.6%	4,921.36	17,003.90	3.42
Java	Indonesia	46.7%	3,906.70	19,875.16	5.10
Gujarat (ref. area)	India	0.2%	15.73	15.25	0.54
Rajasthan (ref. area)	India	0.3%	24.24	77.36	1.07
Sagaing (ref. area)	Myanmar	0.6%	42.20	127.86	0.97
Yunnan (ref. area)	China	2.8%	224.95	837.64	3.46
Pahang (ref. area)	Malaysia	0.4%	30.34	81.31	2.33
Riau (ref. area)	Indonesia	1.4%	120.65	377.70	2.76
Kalimantan (ref. area)	Indonesia	0.9%	71.96	164.81	2.07

yield from each selected area, based on data from EarthStat (Harvested Area and Yield for 4 Crops, EarthStat, accessed in February 2022). The regions where rice accounts for more than 30% of the total area include Punjab, Bihar, Chhattisgarh and West Bengal (India), Bangladesh (the selected area covered almost the entire country, without the big cities), Ayeyarwady (Myanmar), and Java (Indonesia). The reference areas selected for comparison are Gujarat and Rajasthan (India), Sagaing (Myanmar), Yunnan (China), Pahang (Malaysia), Riau and Kalimantan (Indonesia). Areas adjacent to large cities with a population of over 500,000 were excluded from the analysis due to the impact of CH_4 emissions from municipal waste on CH_4 emissions from rice cultivation. Fig. 1 presents a map of the areas included in the study.

2.2. Satellite data

This study used Sentinel–5P data for the period from February 8, 2019 to January 31, 2022. CH_4 measurements are collected as the column average dry air mixing ratio of CH_4 (in ppb–parts per billion) by the on board sensor TROPOMI. All datasets were retrieved from the 'COPERNICUS/S5P/OFFL/L3_CH4' of Google Earth Engine image collection as georeferenced raster files (in GeoTIFF format file) with a spatial resolution of 7 × 7 km. The mean values of the column-averaged dry-air mixing ratio of CH_4 for 1-month periods were analyzed. The only exception was the first period, which was shorter than a full month (February 8–28, 2019).

2.3. Data analysis

Using data from the Google Earth Engine, further analyses were performed to assess long–term and seasonal changes in the CH_4 content in the atmosphere over the study period (February 8, 2019–January 31, 2022). Raster files (GeoTIFF) containing averaged values of the air–methane mixing ratio were used to calculate the average monthly CH_4 emissions for all areas and to generate monthly maps of CH_4 emission. Using the zonal statistics tool in the QGIS 3.18 software (QGIS Development Team, 2022), the average of CH_4 emissions for each high rice concentration area and reference areas for each month were calculated separately for the entire study period.

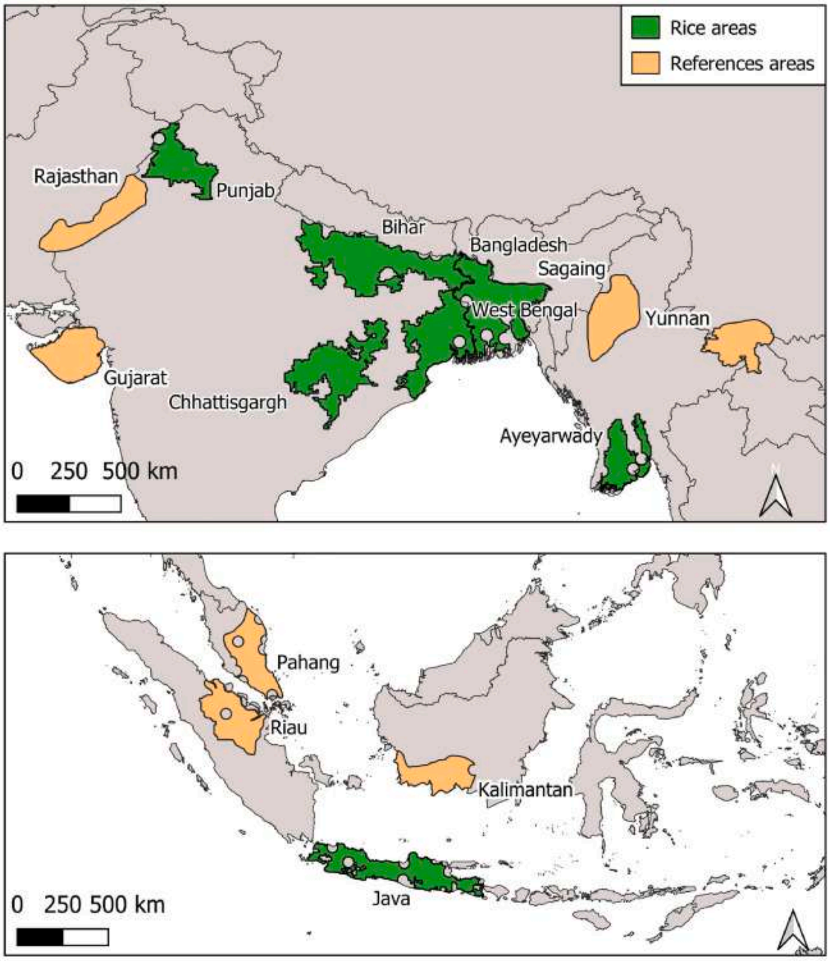

Fig. 1. Study areas with a high concentration of rice above 30% of the total area (green) and a low concentration of rice (reference areas in orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Subsequently, to analyze the temporal changes in the CH_4 content in the atmosphere, a linear regression analysis was performed for each area over the study period. To confirm the statistical significance of the linear regression analysis, a parametric *t*-test was conducted. In addition, a seasonal decomposition of the time series using additive model was performed for monthly atmospheric CH_4 data over the study period. The analysis was conducted for monthly data based on moving average assuming annual cyclicality of methane content changes. The significance of the time series was confirmed using the non-parametric Mann-Kendall test. Results from areas with high rice concentration were compared with reference areas in close proximity to observe the differences and possible similarities related to CH_4 transport in the atmosphere. The areas compared were: Punjab with Gujarat and Rajasthan; Bihar, Chhattisgarh, West Bengal with Sagaing; Bangladesh with Sagaing, Ayeyarwady with Sagaing and Yunnan; Java with Pahang, Riau and Kalimantan.

3. Results

3.1. Mean CH_4 content for the study areas

Table 2 presents the mean CH_4 content in the atmosphere for selected areas in the period under study. The highest CH_4 content was observed in Bangladesh (1914.6 ppb), as well as in Bihar (1912.2 ppb) and West Bengal (1910.1 ppb) – areas in India. The exception was the Indonesian island of Java, where the mean CH_4 content was 1837.8 ppb. Fig. 2 shows the mean CH_4 content in the atmosphere for the studied regions. Differences within the studied areas may result from different geographic locations, including distance from large water reservoirs and altitude. In reference areas with a low share of rice cultivation in the area, lower average CH_4 contents were observed compared to areas with high rice concentration. The only exceptions were the areas of Rajasthan (1917.8 ppb) and Gujarat (1894.0 ppb) located in India. These two regions may have different sources of CH_4 emissions. In the case of Rajasthan, it can be municipal waste. CH_4 emission can be highly dependent on landfills waste (Singh et al., 2018). Gujarat is a region with wetlands, which are one of the most important sources of atmospheric CH_4 (Agarwal and Garg, 2007). The remaining reference areas of Kalimantan, Yunnan and Pahang, also located in the Malaysian Archipelago, despite low average CH_4 contents, were at levels similar to those observed for the Java area and amounted to 1851.1, 1836.3 and 1825.8 ppb, respectively.

3.2. Temporal changes in CH_4

Linear regression equations with temporal trends in the studied period are presented in Table 3. In all study areas, a long-term upward trend in CH_4 content was observed throughout the study period. The mean yearly increase in atmospheric CH_4 content in areas with high rice concentration during the studied period varied from 3.7 ppb in Ayeyarwady (Myanmar) to 19.6 ppb in Bihar (India). For the reference areas (with a lower share of rice) next to the study areas, the mean increase in CH_4 ranged from 8.2 ppb for Sagaing (Myanmar) to 19.9 ppb for Yunnan (China).

Moreover, seasonal changes in atmospheric CH_4 content were observed (Supplementary Figs. 1–36). Seasonal time–series decomposition using moving averages of monthly atmospheric CH_4 data showed a seasonal within–year amplitude of about 15.5 ppb (Fig. 3). The highest monthly average was observed in October and the lowest in July (6.7 ppb higher and 8.8 ppb lower, respectively, compared to the 12-month moving average). The annual amplitude of CH_4 in the atmosphere on a global scale was much lower in comparison to the regions included in the study. Evaluation of seasonal trends is not possible for all areas due to the lack of complete data. Complete data covered Punjab and Bihar – rice regions, and Rajasthan (reference region with a lower share of rice) in India. For regions in India, the annual amplitude of CH_4 content based on the seasonal decomposition of a time series additive model from monthly data was very high i.e., about 56 ppb for the Punjab region, about 58 ppb for Bihar and 47 ppb for Rajasthan (reference area). Based on additive seasonal decomposition, the highest content of CH_4 was recorded in September (about 25–34 ppb above the annual average) and the lowest in February–March in case of Punjab, and in February–June in Bihar (about 22–27 ppb below the annual average).

Table 2
Mean CH_4 concentration in the atmosphere throughout the study period (February 8, 2019–January 31, 2022) for each selected area.

Region	Country	Atmospheric CH_4 content (ppb)
Punjab	India	1903.3
Bihar	India	1912.2
Chhattisgarh	India	1899.5
West Bengal	India	1910.1
Bangladesh	Bangladesh	1914.6
Ayeyarwady	Myanmar (Burma)	1900.8
Java	Indonesia	1837.8
Gujarat (ref. area)	India	1894.0
Rajasthan (ref. area)	India	1917.8
Sagaing (ref. area)	Myanmar (Burma)	1876.8
Yunnan (ref. area)	China	1854.1
Pahang (ref. area)	Malaysia	1851.1
Riau (ref. area)	Indonesia	1836.3
Kalimantan (ref. area)	Indonesia	1825.8

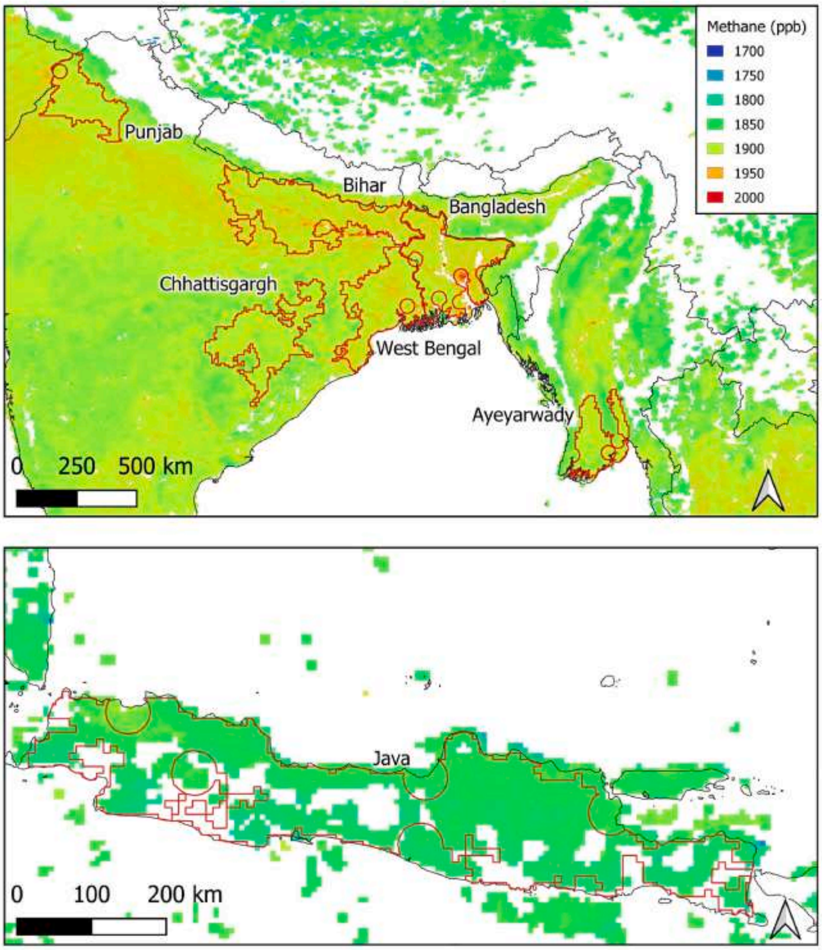

Fig. 2. Mean CH_4 content for the main areas for the entire study period based on data from (Google Earth Engine, accessed on February 2022).

Table 3
Regression equation presenting relationships between CH_4 content (y) and subsequent months in the entire study period (x).

Region	Country	Linear regression	*P*-value[a]
Punjab	India	y = 1.3245x + 1871.8	< 0.01
Bihar	India	y = 1.6333x + 1877.9	0.02
Chhattisgarh	India	y = 1.3233x + 1867.3	< 0.01
West Bengal	India	y = 1.5971x + 1875.0	< 0.01
Bangladesh	Bangladesh	y = 1.5134x + 1878.5	< 0.01
Ayeyarwady	Myanmar	y = 0.3069x + 1887.1	0.37
Java	Indonesia	y = 0.8277x + 1823.7	< 0.01
Gujarat (ref. area)	India	y = 1.3720x + 1867.7	< 0.01
Rajasthan (ref. area)	India	y = 1.2944x + 1887.4	< 0.01
Sagaing (ref. area)	Myanmar	y = 0.6830x + 1868.3	0.054
Yunnan (ref. area)	China	y = 1.6565x + 1824.7	< 0.01
Pahang (ref. area)	Malaysia	y = 0.7805x + 1828.5	0.053
Riau (ref. area)	Indonesia	y = 0.8012x + 1819.6	0.11
Kalimantan (ref. area)	Indonesia	y = 0.7025x + 1815.4	0.09

[a] Significant trend is observed, if the *P*-value < 0.05.

3.3. The comparison of CH_4 contents between main and references regions

The results for the monthly mean CH_4 contents in each area are presented in Tables 4 and 5 and a comparison of temporal changes in CH_4 between regions are shown in Supplementary, Fig. 37. In India, the highest annual increase was observed in Bihar – 19.6 ppb (1.63 ppb per month) and West Bengal with 19.2 ppb (1.60 ppb per month), while in Chhattisgarh the increase in CH_4 content was 15.9 ppb per year (1.32 ppb per month). The nearest reference area was Sagaing (Region of Myanmar), which recorded the smallest annual increase of 8.2 ppb (0.7 ppb per month), significantly lower compared to Bihar, West Bengal and Chhattisgarh. In Punjab

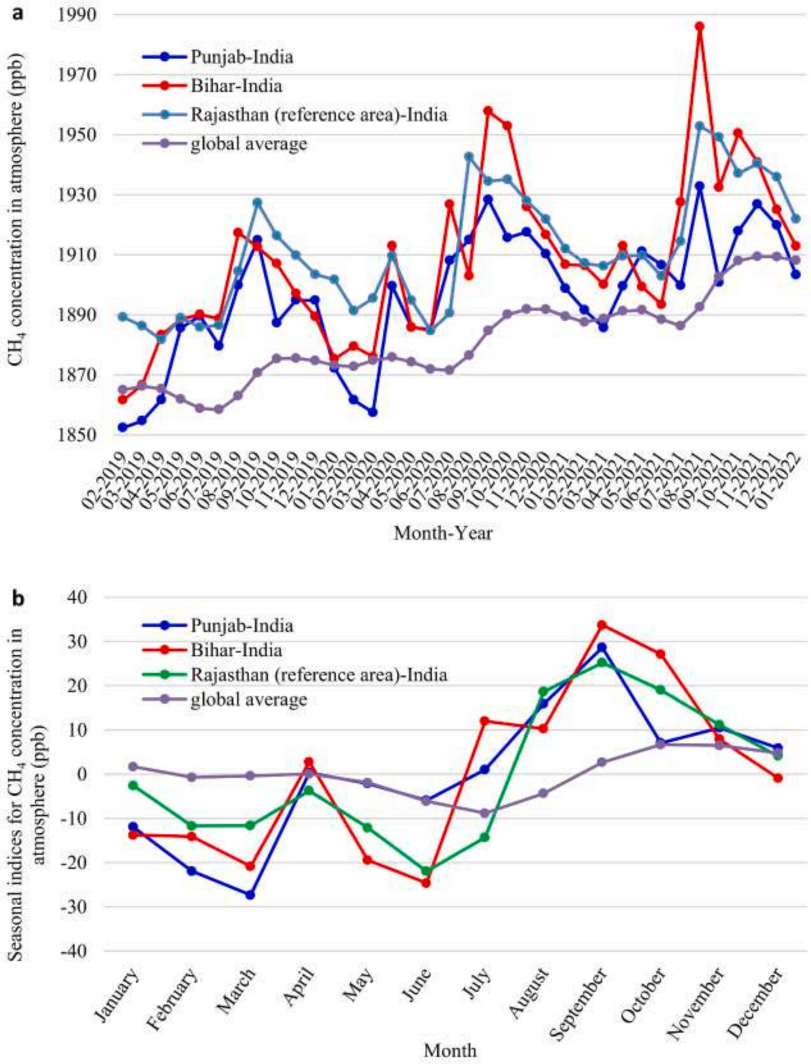

Fig. 3. Monthly average CH_4 concentration in the atmosphere for selected regions and for the global scale (a) and seasonal indices based on decomposition of time series (additive model) by moving averages (b). All seasonal trends were significant, according to the Mann-Kendall test ($P < 0.001$).

(North–West India), the annual increase in CH_4 concentration was 15.9 ppb (1.32 ppb per month), but this increase was comparable to the increase in CH_4 in the nearest reference areas, i.e., Gujarat and Rajasthan, 16.5 ppb per year (1.37 ppb per month) and 15.5 ppb per year (1.29 ppb per month), respectively. Another area with a large annual CH_4 increase of 18.2 ppb (1.5 ppb per month) was Bangladesh, which was significantly greater than the increase in the comparable reference area of Sagaing. In the next study area, Java (Indonesia), the annual increase in CH_4 content was much lower than in Indian regions – 9.9 per year (0.83 ppb per month). Java's annual CH_4 increase was similar to neighboring reference areas located in Indonesia i.e., Pahang (9.4 ppb), Riau (9.6 ppb) and Kalimantan (8.4 ppb). The smallest increase in atmospheric CH_4 content for the studied regions was observed in the Ayeyarwady area, which amounted to 3.7 ppb per year (0.3 ppb per month). This area also had the highest number of missing data of any main areas, which may have affected the results.

4. Discussion

A long-term increase in emissions was observed in all regions included by the study. The mean yearly increase in atmospheric CH_4 content in areas with high rice concentration during the studied period was highest in Bihar (India) – 19.6 ppb and lowest in Ayeyarwady (Myanmar) – 3.7 ppb. In comparison, for the reference areas, the mean CH_4 increase varied from 8.2 ppb in Sagaing (Myanmar) to 19.9 ppb in Yunnan (China). Global Monitoring Laboratory results show that the average global increase in CH_4 from February 2019 to January 2022 was 15.6 ppb (regression coefficient based on monthly data is equal to 1.3 ppb) (Department of Commerce, N., 2022). According to this data, several regions, particularly those in India and Bangladesh, showed higher increase compared to the global average. However, the long-term mean annual increase, in several regions with a high share of rice

Table 4
Mean CH_4 content for selected areas with high rice concentration based on Sentinel–5P data (in ppb).

Region	Punjab	Bihar	Chhattisgargh	West Bengal	Bangladesh	Ayeyarwady	Java
8-28/02/2019	1852.4	1861.6	1871.4	1874.5	1871.3	1868.7	1816.3
1-31/03/2019	1854.7	1866.6	1875.1	1877.2	1883.6	1880.6	1819.8
1-30/04/2019	1861.7	1883.3	1875.2	1875.4	1881.9	1876.8	1822.2
1-31/05/2019	1885.6	1888.6	1868.9	1863.8	1865.9	1874.8	1828.3
1-30/06/2019	1889.6	1890.1	1871.1	1876.7	1872.6	–	1820.8
1-31/07/2019	1879.6	1888.7	1847.1	1852.3	1866.5	–	1826.0
1-31/08/2019	1899.9	1917.3	–	–	1881.4	–	1829.4
1-30/09/2019	1914.9	1912.6	1840.3	1911.8	1934.3	1937.6	1835.4
1-31/10/2019	1887.3	1907.0	1926.0	1938.9	1947.2	1929.0	1841.8
1-30/11/2019	1894.9	1897.1	1895.6	1898.8	1900.3	1887.8	1836.5
1-31/12/2019	1894.8	1889.4	1884.0	1892.9	1887.5	1889.1	1832.7
1-31/01/2020	1872.2	1875.3	1877.4	1890.4	1888.3	1875.6	–
1-29/02/2020	1861.6	1879.5	1878.6	1887.0	1886.9	1878.1	–
1-31/03/2020	1857.5	1876.0	1885.2	1886.7	1894.6	1893.3	1826.7
1-30/04/2020	1899.6	1913.0	1911.5	1910.9	1916.1	1894.5	1854.5
1-31/05/2020	1885.8	1885.9	1877.3	1873.5	1878.4	1877.0	1836.0
1-30/06/2020	1885.1	1884.7	1868.0	1858.2	1861.2	–	1834.3
1-31/07/2020	1908.1	1926.8	–	–	–	–	1836.3
1-31/08/2020	1915.0	1903.0	1851.4	–	1903.4	–	1847.5
1-30/09/2020	1928.4	1957.8	1923.1	1963.1	1940.8	–	1840.5
1-31/10/2020	1915.7	1952.9	1935.8	1962.3	1965.6	1900.7	1842.2
1-30/11/2020	1917.6	1926.0	1920.2	1928.9	1923.3	1916.4	1836.3
1-31/12/2020	1910.3	1916.7	1904.1	1920.5	1918.9	1901.0	–
1-31/012021	1898.8	1906.8	1902.1	1916.1	1915.7	1897.7	–
1-28/02/2021	1891.6	1906.4	1895.7	1907.1	1908.8	1901.9	1858.5
1-31/03/2021	1885.7	1900.1	1894.0	1909.0	1918.4	1903.8	–
1-30/04/2021	1899.6	1913.0	1911.5	1910.9	1916.1	1894.5	1854.5
1-31/05/2021	1911.1	1899.3	1887.4	1881.7	1889.6	1893.0	1850.1
1-30/06/2021	1906.6	1893.4	1875.1	1852.0	1874.6	1872.0	1842.9
1-31/07/2021	1899.8	1927.6	1888.1	1936.7	1893.7	–	1843.1
1-31/08/2021	1932.8	1986.0	1928.4	1953.6	1973.7	1858.5	1845.0
1-30/09/2021	1900.8	1932.4	1888.5	1916.7	1928.8	1869.3	1847.2
1-31/10/2021	1917.9	1950.5	1929.4	1954.1	1963.7	1895.6	1856.6
1-30/11/2021	1926.9	1940.8	1922.8	1939.4	1936.5	1915.3	–
1-31/12/2021	1919.9	1925.0	1916.1	1926.3	1920.8	1917.9	1855.4
1-31/01/2022	1903.3	1912.9	1910.4	1919.6	1917.2	1905.9	1836.6

(Ayeyarwady and Java), was relatively low. Those differences in the increase in CH_4 content between studied areas with high rice concentration may be due to national trends in rice production. Rice production in India and Bangladesh continues to increase, according to FAOSTAT data. Whereas, Myanmar and Java have reported a decline in rice production since 2018 (FAO STAT, accessed in June 2022).

Although the reference areas were included in the study as non-rice cultivation regions, some of the results of CH_4 content in the atmosphere were similar to those of the main regions. For example, the mean CH_4 content in the atmosphere over the entire study period as well as the mean annual increase in Gujarat and Rajasthan (India) were similar to those observed elsewhere in India. These results are due to the mining of lignite, which accounts for 11% of anthropogenic methane emissions into the atmosphere (Sadavarte et al., 2021; Saunois et al., 2020). Whereas in Yunnan, CH_4 emissions from forest vegetation may contribute to mean CH_4 content and a large increase in emissions. This southern part of China has the most diverse mountainous areas in terms of climate and biology, which contributes to higher CH_4 emissions to the atmosphere (Gong and Shi, 2021; Zhou et al., 2018).

In addition to the long–term trend, there is a seasonal trend in CH_4 content. In the study, a seasonal time–series decomposition was calculated using moving averages for monthly CH_4 data in the atmosphere on a global scale for the study period, which confirmed a seasonal within–year amplitude of about 15.5 ppb (lowest in July and highest in October). The same analysis was performed for the studied regions with high rice concentration. Only three regions (Punjab, Bihar and Rajasthan) were included due to incomplete data in the other studied regions. For the studied regions, a very high annual amplitude of CH_4 content was observed (within year difference of about 47–58 ppb, which is more than three times greater compared to global scale data). The highest CH_4 content occurs at the beginning of rice harvest in the typical crop calendar for rice–growing regions in northern India, including Punjab and Bihar, in September and October (Matthews et al., 1995). This is in line with studies by Zhang et al. (2016) and Ito et al. (2022). The highest estimated CH_4 emissions for India and China were found during the period of intensive rice growth, during the summer season, with peak emissions in August and September. Seasonal variation of CH_4 for studied regions was similar to other regions of the word, but some differences were observed. A similar study conducted for regions of China showed the highest content of CH_4 in August or September, but the lowest in January or February (Zhang et al., 2022). The highest and lowest CH_4 contents were observed in China at a similar period or slightly earlier than in India. The amplitude between the lowest and highest CH_4 contents in the studied regions in China was about 40–60 ppb. However, the overall amplitude of China was significantly lower, about 15 ppb (Qin et al., 2022). In

Table 5
Mean CH_4 content for selected reference areas with a low share of rice based on Sentinel–5P data (in ppb).

Region	Gujarat (ref. area)	Rajasthan (ref. area)	Sagaing (ref. area)	Yunnan (ref. area)	Pahang (ref. area)	Riau (ref. area)	Kalimantan (ref. area)
8-28/02/2019	1874.1	1889.2	1844.6	1814.0	1852.1	–	–
1-31/03/2019	1872.6	1886.3	1858.4	1831.7	1839.3	1830.6	1827.3
1-30/04/2019	1864.3	1881.7	1869.7	1828.6	1832.0	–	–
1-31/05/2019	1861.5	1889.0	1860.6	1844.5	1826.0	1820.3	1807.4
1-30/06/2019	1855.3	1885.9	1869.3	–	1812.3	1804.5	1831.8
1-31/07/2019	–	1886.5	–	–	–	–	1805.8
1-31/08/2019	–	1904.5	1872.7	–	–	–	1821.8
1-30/09/2019	–	1927.3	1918.9	–	1817.9	1812.7	1806.5
1-31/10/2019	1900.3	1916.3	1922.9	1863.3	1826.9	1802.1	1823.2
1-30/11/2019	1896.2	1909.8	1864.8	1843.5	–	1868.1	1820.9
1-31/12/2019	1886.2	1903.4	1858.2	1842.1	–	–	–
1-31/01/2020	1880.3	1901.7	1854.2	1819.0	–	1850.7	–
1-29/02/2020	1881.4	1891.4	1855.2	1824.4	–	–	–
1-31/03/2020	1881.5	1895.5	1866.3	1844.2	1849.4	1831.6	–
1-30/04/2020	1897.7	1909.6	1894.3	1865.9	1872.8	–	1842.9
1-31/05/2020	1870.3	1894.8	1874.1	1842.2	–	–	–
1-30/06/2020	1869.5	1884.7	–	–	–	1808.9	–
1-31/07/2020	–	1890.6	–	–	–	–	1806.2
1-31/08/2020	–	1942.6	1886.4	–	1826.5	1838.3	1816.7
1-30/09/2020	1936.1	1934.5	1915.4	–	–	1821.7	–
1-31/10/2020	1922.8	1935.1	1914.2	1887.6	1826.5	1833.6	–
1-30/11/2020	1919.0	1927.9	1891.0	1883.3	–	–	–
1-31/12/2020	1905.2	1921.8	1877.0	1861.2	–	1861.2	–
1-31/012021	1904.7	1912.0	1875.5	1848.4	1861.7	–	1868.3
1-28/02/2021	1893.8	1907.2	1872.3	1851.5	1869.8	–	1877.3
1-31/03/2021	1892.1	1906.2	1882.6	1855.3	–	1875.3	1843.8
1-30/04/2021	1897.7	1909.6	1894.3	1865.9	1872.8	–	1842.9
1-31/05/2021	1884.6	1909.8	1890.4	1859.0	1843.2	1853.6	1836.4
1-30/06/2021	1885.7	1902.9	–	–	1816.6	1830.6	1818.4
1-31/07/2021	1892.9	1914.5	–	–	1835.4	1828.0	1822.9
1-31/08/2021	–	1952.8	–	–	1818.0	–	1775.8
1-30/09/2021	1919.2	1949.2	1876.0	1885.7	1842.8	1832.7	1835.4
1-31/10/2021	1920.0	1937.1	1909.3	1908.5	1852.3	1841.6	1835.5
1-30/11/2021	1924.8	1940.4	1895.2	1892.3	1841.5	–	1844.5
1-31/12/2021	1921.2	1935.9	1874.5	1893.8	1893.2	1802.3	1870.2
1-31/01/2022	1911.9	1921.9	1877.3	1849.0	1889.3	1892.9	1834.8

China, the mean annual increase of CH_4 for the 2018–2021 period ranged from 4.5 to 10.6 ppb, depending on the region. Growth was much lower compared to all rice-growing regions included in this study i.e., regions in India, Bangladesh and Indonesia. The only exception was Myanmar, where increase was very low. In the study for Thessaloniki, Greece (Mermigkas et al., 2021), for 2019–2021, the annual CH_4 amplitude was about 40 ppb, while the lowest CH_4 content in the atmosphere was observed in early spring (March–April) and the highest in autumn and winter (September–December). The annual amplitude was lower compared to the studied rice regions, and the highest CH_4 content was observed later compared to the typical peak CH_4 content for rice regions.

The transport of CH_4 over long distances in the atmosphere depends on wind speed and direction. In this study, it is difficult to evaluate direction of CH_4 transport, because emissions from rice per unit area are relatively small and cover large areas. In the study by Crosman (2021), the transport of CH_4 was evaluated in Permian Basin, the largest oil and second-largest natural gas producing region in the United States. Observations with Sentinel–5P allowed to evaluate directions of CH_4 transport in various meteorological conditions. In addition to the impact of meteorological conditions, the transport of CH_4 was also influenced by the terrain. Long–distance transportation of CH_4 is mainly along parallels of latitude because of prevailing winds. The worldwide distribution of CH_4 confirms that similar content of CH_4 is found at the same latitudes (Hu et al., 2018). In the case of India, the transport and seasonality of atmospheric methane content are influenced by the monsoon season. In the study by Chandra et al. (2017) based on GOSAT data, seasonal changes in CH_4 content in the northern and southern parts of India were observed. These changes occurred during the peak of the southwestern monsoon (July–September) and early autumn (October–December) seasons.

The aim of the study was to investigate the long-term trend and seasonal variability in CH_4 concentration for areas of intensive rice cultivation and to compare them to the results of reference regions (with a very low share of rice cultivation). Determining the amount of atmospheric CH_4 emissions from areas with high rice production using satellite instruments is important in efforts to mitigate GHG emissions. Mitigation strategies can include optimization of crop management including water management, fertilization and cultivar selection (Lu et al., 2000). Moreover, proper management of rice straw, attention to the roots and exudates of rice roots in wetlands can also influence CH_4 emission (Neue et al., 1996).

5. Conclusions

In the studied period from February 2019 to January 2022, the average annual increase in atmospheric CH_4 content in areas with a high concentration of rice was the highest in India (from 15.9 to 19.6 ppb per year). A similar annual increase in CH_4 content was observed in Bangladesh (18.2 ppb). The values were higher than the global average annual increase (15.8 ppb). By contrast, Ayeyarwady (Myanmar) and Java (Indonesia) had much lower annual growth rates of 3.7 and 9.9 ppb, respectively.

The seasonal variability of CH_4 content in the atmosphere was characterized by a very large annual amplitude in the rice regions of India. For Punjab, Bihar and Rajasthan, the results were about 56, 58 and 47 ppb, respectively. The annual amplitude was much higher in comparison to the global amplitude (15.5 ppb). Seasonal variability in atmospheric CH_4 content is consistent with CH_4 emissions during a typical growth cycle of rice in Southeast Asia. The highest content of CH_4 is observed in late summer i.e., before the rice harvest.

With a growing rice demand, rice production must increase in the future. This can be achieved by intensifying rice production in existing rice areas. At the same time, however, options to reduce CH_4 emissions from rice cultivation should be assessed, especially in regions with a high share of rice cultivation in total crop production, which were evaluated in the study. The use of satellite remote sensing to analyze GHG emissions is an innovative approach to spatial-temporal evaluation of methane emissions, which allows to monitor the phenomena on a regional and global scale.

Ethical statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2023.100972.

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Niniejszym oświadczam, że w pracy Kozicka, K., Orazalina, Z., Gozdowski, D., Wójcik-Gront, E. 2023. Evaluation of temporal changes in methane content in the atmosphere for areas with a very high rice concentration based on Sentinel-5P data. *Remote Sensing Applications: Society and Environment*, 30, 100972, mój indywidualny udział w jej powstaniu polegał na opracowaniu założeń metodycznych, przetwarzaniu danych oraz przygotowaniu oryginalnego tekstu pracy. Udział procentowy szacuję na 70%.

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Statement of co-authorship

I hereby declare that in the work Kozicka, K., Orazalina, Z., Gozdowski, D., Wójcik-Gront, E. 2023 Evaluation of temporal changes in methane content in the atmosphere for areas with a very high rice concentration based on Sentinel-5P data. *Remote Sensing Applications: Society and Environment*, 30, 100972, my individual contribution to it consisted of participation in the preparation of the data for the paper. I estimate the percentage contribution at 5%.

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Explaining Global Trends in Cattle Population Changes between 1961 and 2020 Directly Affecting Methane Emissions

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Abstract: Methane (CH_4) emissions from agricultural sources contribute significantly to the total anthropogenic greenhouse gas emissions, which cause climate change. According to the guidelines of the International Panel on Climate Change (IPCC) for calculating greenhouse gas emissions, agriculture is responsible for approximately 10% of total CH_4 emissions from anthropogenic sources. CH_4 is primarily emitted from livestock farming, particularly from cattle production during enteric fermentation and from manure. This article describes the results of multivariate statistical analyses carried out on data collected from 1961 to 2020 for thirty countries with the largest cattle populations. The study evaluated the trends in temporal changes in cattle populations and identified groups of countries with similar patterns during the study period. The global cattle population was highly correlated with CH_4 emissions from the enteric fermentation of cattle and their manure. The countries experiencing the largest increase in cattle population were primarily developing countries located in South America, Africa and Southeastern Asia. The cattle population in these countries showed a strong correlation with the human population. On the other hand, the countries where the cattle population remained stable during the study period were mainly highly developed countries. The correlations between most of the examined variables associated with cattle production and the cattle population in these countries were inconsistent and relatively weak. In the near future, further increase in the cattle population and the associated CH_4 emissions are expected, mainly in developing countries with high population growth.

Keywords: enteric fermentation; agriculture; long-term changes; multivariate relationships

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1. Introduction

One of the main greenhouse gases (GHGs) that contribute to global warming and climate change, alongside carbon dioxide and nitrous oxide, is methane (CH_4) [1]. Despite being present in the atmosphere in smaller quantities than carbon dioxide, CH_4 has a 100-year global warming potential 25 times greater than carbon dioxide due to its higher ability to absorb infrared radiation [2,3]. CH_4 is released from various sources, including landfills, waste management, energy production from coal, oil, and natural gas mining and processing [4]. It is also associated with agricultural practices. The concentration of CH_4 in the atmosphere has increased 2.5 times since pre-industrial times, primarily due to the intensive use of fossil fuels and the growth of ruminant farming, landfills, and rice fields, in line with the expansion of the human population [3,5]. Agricultural sector emissions account for approximately 25% of total global anthropogenic emissions, with direct emissions from agriculture estimated to constitute about 10–12% of total global GHG emissions in 2010 [6,7]. Additional indirect emissions result from deforestation, energy use, and the production of animal feed [8]. Livestock, particularly ruminants such as cattle, contribute the majority of direct agricultural emissions [9,10]. Therefore, reducing livestock emissions is crucial for achieving ambitious global mitigation targets [11,12].

The International Panel on Climate Change (IPCC) provides guidelines for estimating livestock emissions [2,13]. Animals are typically categorized by species because the type of digestive system significantly influences CH_4 emissions. Ruminant species such as cattle are the main source of CH_4 emissions due to their intensive food fermentation [14]. CH_4 emissions from manure management are usually lower than those from enteric fermentation [15]. Under anaerobic conditions, manure decomposition leads to substantial CH_4 production [2].

As estimated emissions are directly proportional to the cattle population (emission = emission factor $\times$ number of cattle) [14], the countries with the highest cattle population are the primary contributors to methane emissions from agricultural sources. The main regions for cattle production are South and North America, as well as Southeastern Asia. Cattle production varies in intensity and efficiency across different regions [16]. Developing countries often have lower productivity in terms of milk and beef, resulting in higher CH_4 emissions per unit of milk or beef compared to developed countries. However, developing countries may have lower CH_4 emissions per head of cattle due to less intensive production, including poorer nutrition. For example, the annual milk yield per cow in the US is approximately six times higher than in India or Pakistan [17]. GHG output (kg of CO_2 equivalents per kg of milk) ranges from 1.3 for developed countries like the USA to 7.4 for central African countries. The same level of milk or beef production can be achieved with a lower cattle population and higher production efficiency or with a higher cattle population and lower production intensity. The growing world population necessitates increased food production, including milk and beef, which can be achieved by increasing the cattle population or improving efficiency. Despite the gradual shift towards plant-based diets, the global demand for milk and beef continues to rise. Therefore, it is crucial to maintain sustainable cattle production [18]. Milk and beef production are closely connected, with dairy-beef accounting for 45% of global beef production, depending on the region [9]. The specific conditions of cattle production in different regions lead to varying changes in the cattle population, influenced by production intensity and the demand for milk and beef. On-farm practices aimed at CH_4 mitigation are more likely to focus on reducing emissions per unit of milk or meat rather than individual animal emissions [19]. Mitigation strategies that do not hinder production while effectively reducing CH_4 emissions in cattle are necessary. In practice, sustainable cattle production should be economically viable, ensuring high efficiency and low emissions per unit of production [20]. Previous studies have demonstrated that increased livestock production contributes to higher CH_4 emissions unless effective strategies to mitigate GHG emissions in livestock systems are implemented [21].

The primary objective of this study is to analyze worldwide trends in cattle populations. Methane emissions and cattle population trends are closely interconnected, as the size and management of cattle populations directly impact methane emissions from the livestock sector. An increasing cattle population generally leads to higher methane emissions. As more cattle are raised for meat and dairy production, the overall methane output from enteric fermentation and manure management tends to rise. Thus, the investigation goals are to identify countries that exhibit similar trends in cattle populations over the past 60 years (1961–2020) and examine the factors associated with these trends. It is expected that countries will fall into categories of growing, stable or declining cattle populations, influenced by various factors such as economic conditions, government policies, environmental concerns and shifts in consumer preferences. Furthermore, this research aims to identify specific variables related to cattle breeding that can effectively characterize the selected groups of countries. The study also includes a comprehensive analysis of CH_4 emissions specifically attributed to livestock through enteric fermentation and manure management.

2. Materials and Methods

Data from The Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) [22] spanning the period from 1961 to 2020 were utilized to examine shifts in the global cattle population. The analysis focused on 30 countries that had existed since 1961 and possessed a cattle population of at least 10 million heads. These 30 countries include: Argentina (ARG), Australia (AUS), Bangladesh (BGD), Bolivia (BOL), Brazil (BRA), Burkina Faso (BFA), Canada (CAN), Chad (TCD), China (CHN), Colombia (COL), France (FRA), Germany (DEU), India (IND), Indonesia (IDN), Kenya (KEN), Mali (MLI), Mexico (MEX), Myanmar (MMR), New Zealand (NZL), Niger (NER), Nigeria (NGA), Pakistan (PAK), Paraguay (PRY), South Africa (ZAF), Turkey (TUR), Uganda (UGA), United Republic of Tanzania (TZA), the United States of America (USA), Uruguay (URY), Venezuela (VEN) (Figure 1). The combined cattle population of these countries accounted for over 70% of the global cattle population in 2020 [22]. Therefore, the trends observed in these analyzed countries will significantly influence the overall trends in the global cattle population.

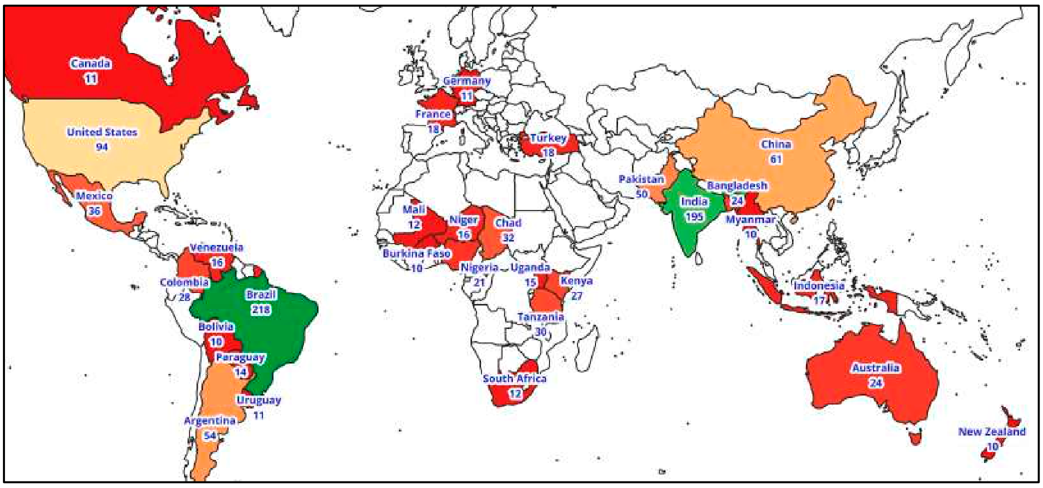

Figure 1. Countries selected for the analyses and their cattle population in millions of heads in 2020.

The data analyzed included the following variables related to the cattle population: size of the cattle population (CT), agricultural land (AL), farm machinery (FM), GDP per capita (GDP), land under permanent meadows and pastures (LMP), beef consumption per capita (MBC), total meat consumption per capita (MTC) including fish and seafood, milk consumption per capita (MC), milk yield per animal (MYA), rural population percent (RPP), total population (TP) and two ratios based on cattle population, cattle/agricultural land (CT/AL) and cattle/total population (CT/TP). The data also included CH_4 emissions from cattle enteric fermentation and manure management (CH_4).

To compare trends in the size of a country's cattle population, an increment (*I*) was used instead of absolute numbers of animals. The increment is calculated using the formula:

$$I = \frac{y_{i+1} - y_i}{y_i}$$

where i represents the decade number, starting from the first decade of the analysis (1961–1970) denoted by y_i. The last decade is 2011–2020.

The data on CH_4 emissions from enteric fermentation and manure management were obtained from the FAOSTAT database. The calculations were performed using the Tier 1 method, separately for dairy cattle and non-dairy cattle [2,22]. The Tier 1 method, as outlined in the 2006 IPCC guidelines, is a simplified approach for estimating CH_4 emissions from enteric fermentation and manure management. It provides a basic methodology that can be applied at the country level, taking into account factors such as livestock population, feed intake, CH_4 conversion rates and regional characteristics like climate region or temperature. The FAOSTAT database provides CH_4 emission data from enteric fermentation and manure management by country, covering the period from 1961 to 2020. CH_4 emissions from enteric fermentation are a significant component of the overall GHG emissions from the agricultural sector. The emissions factors (EFs) values for enteric fermentation depend on the livestock type (dairy cattle and non-dairy cattle) and regional grouping specified in IPCC guidelines, Table 10.11 [2]. The EF values for manure management assigned to each country depend on the region and the country average annual temperature. The EF values applied for cattle were taken from IPCC Table 10.14 [2]. The methane emission factors from enteric fermentation and manure management used are presented in Table 1.

Table 1. The methane emission factors from enteric fermentation and manure management used in the study.

	CH_4 Emission Factor [kg head^{-1} per year]		Countries Using Presented Value
	Enteric Fermentation	**Manure Management**	
dairy	46	1 (2 TUR)	BFA, KEN, MLI, NER, NGA, TCD, TUR, TZA, UGA, ZAF—Countries of Africa and Middle East
non-dairy	31	1	
dairy	58	5	BGD, IND, PAK Countries of Asia
non-dairy	27	2	
dairy	68	9 CHN, 27 IDN, 23 MMR	CHN, IDN, MMR Countries of Asia
non-dairy	47	1	
dairy	72	1 (2 VEN)	ARG, BOL, BRA, COL, MEX, PRY, URY, VEN Latin America and Caribbean
non-dairy	56	1	
dairy	90	23 NZL, 29 AUS	AUS, NZL Countries of Oceania
non-dairy	60	1 NZL, 2 AUS	
dairy	117	21 DEU, 22 FRA	DEU, FRA Countries of Europe
non-dairy	57	6 DEU, 7 FRA	
dairy	128	48	CAN, USA Countries of North America
non-dairy	53	1	

Cattle production varies across regions of the world due to various factors such as climate, geography, cultural practices, and economic conditions. The IPCC methodology recognizes that different regions exhibit distinct characteristics in cattle production, which in turn influence the values of emission factors used. In Africa extensive grazing systems are common, with cattle often raised in open pasturelands. Many cattle breeds are adapted to withstand heat and tropical diseases. In Asia diverse cattle production systems exist, including intensive, semi-intensive and extensive systems. In Europe cattle production systems vary from intensive indoor systems to extensive grazing on pasturelands. Dairy farming is a significant focus, with specialized dairy breeds and high milk yields. In Latin America and Caribbean extensive grazing systems and large-scale ranching are common, especially in countries like Brazil and Argentina. In North America cattle production involves a mix of intensive feeding and extensive grazing systems. Dairy farming is also significant, particularly in the United States and Canada. In Oceania, cattle production revolves around extensive grazing systems on large pasturelands. Dairy farming is significant in countries like Australia and New Zealand.

The analysis of obtaining groups with homogeneous countries in terms of the cattle change trend was performed using cluster analysis. This approach facilitates the identification of essential features based on the population trend analysis of each group. Ward's method, which is based on a variance approach, was applied in the cluster analysis as it is considered very effective [23]. The square of the Euclidean distance was used to calculate the multivariate distance between objects, giving more weight to objects that are farther apart. Correlation coefficients were used to evaluate the relationships between selected variables and the cattle population or the cattle population per agricultural land or per human population. Regression analysis was also performed to evaluate the temporal trends of the cattle population, as well as the cattle population per agricultural land or per human population. Additionally, principal component analysis (PCA) was employed to assess the multivariate differences between the studied countries and the relationships between variables included in the study. The results of PCA were presented graphically as a biplot. The analyses were conducted using Statistica 13 (Tibco Software Inc., Palo Alto, CA, USA). The significance level for all the tests was set at 0.05.

3. Results

3.1. Temporal Trends in Cattle Population in Period 1961–2020

In 1961, the global cattle population was approximately 942 million. In 2020, it had reached around 1523 million heads. When plotting the changes in the number of cattle over time, the average annual increase is approximately 8.3 million and can be well described by a linear function (R^2 = 0.95) (Figure 2a). The increase in the cattle population correlates with the rise in cattle density, represented as the number of cattle heads per 1000 ha of agricultural land. However, the growth rate of the cattle population (about 62% during the study period) surpassed the increase in the cattle-to-agricultural land ratio (about 51%), as depicted in Figure 2. The number of cattle heads per 1000 people exhibited a linear decrease (R^2 = 0.98) during the study period, declining from 307 to 194 (a reduction of approximately 37%). The downward trend in recent years has been slower. CH_4 emission associated with cattle production, including both enteric fermentation and manure, were strongly correlated with the cattle population (Figure 2b). The average yearly global increase in CH_4 emissions during the study period amounted to 0.34 million tons. The relationship between cattle population and methane emission from cattle worldwide was nearly linear (Figure 2c). Based on the regression analysis, it was determined that an increase in the cattle population by one head results in an average annual increase in CH_4 emissions of 42.7 kg.

Temporal trends of the cattle population and its ratio per agricultural land or per number of people varied significantly among different countries. To evaluate these changes from 1961 to 2020, the means for decades (1961–1970 and 2011–2020) were calculated. Decade means were used because the values for individual years were highly variable in some countries, such as Germany, where recent data exhibited significant year-to-year variability. The changes between the first decade (1961–1970) and the last decade (2011–2020) are presented in Table 2. The highest increase in the cattle population was observed in Chad (488% higher cattle population in the last decade compared to the first decade). Bolivia and Burkina Faso also experienced increases of over 300% in their cattle population, while Brazil, Niger, Paraguay and Uganda saw increases in the range of 200–300%. Most of the studied countries exhibited an increase in their cattle population, with only three countries experiencing a decrease: Germany (−33%), France (−9%) and the USA (−14%). The area of agricultural land remained relatively stable over time, and the ratio of cattle population to agricultural area was generally higher in the last decade (1961–1970) compared to the first decade (2011–2020).

The number of cattle per 1000 people decreased in most countries, with the strongest decreases observed in Bangladesh (−67%), India (−63%), Turkey (−61%) and South Africa (−66%). Only four countries showed an increase in the cattle population-to-number of people ratio: Burkina Faso (39%), Bolivia (60%), Brazil (10%) and Chad (64%).

To identify groups of countries with similar patterns of cattle population changes, a cluster analysis was conducted. The analysis used mean increments calculated for subsequent decades (1961–1970, . . . , 2011–2020) based on the formula presented in the Material and Methods section. Since data for the first decade (1961–1970) did not have associated data for the previous decade (1951–1960), five variables were used for the analysis, with the first variable representing the decade 1971–1980 and the last variable representing the decade 2011–2020. The cluster analysis identified four groups of countries, as shown on the dendrogram in Figure 3. The patterns of changes in cattle population over time are presented in Figure 4, and the groups of countries are displayed on the map in Figure 5, along with the percentage change in cattle population between 1961–1970 and 2011–2020. The first group of countries consisted of four countries from central Africa, Burkina Faso, Mali, Niger, Uganda, and one country from south Asia–Pakistan. These countries experienced a high increase in cattle population, particularly in the last two decades (2001–2020). A similar pattern of cattle population changes was also observed in Chad, which was atypical due to the highest increase in cattle population throughout the entire study period, especially in the decade 1991–2000 (approximately 220%). The second group of countries included Bolivia, Brazil, Venezuela, Paraguay, Mexico (South America and the southern part of North America), Indonesia, Myanmar (Southeastern Asia), Kenya, Nigeria and Tanzania (Central Africa). These countries exhibited a relatively stable increase in the cattle population throughout the study period, with slightly higher increases in the first half compared to the second half.

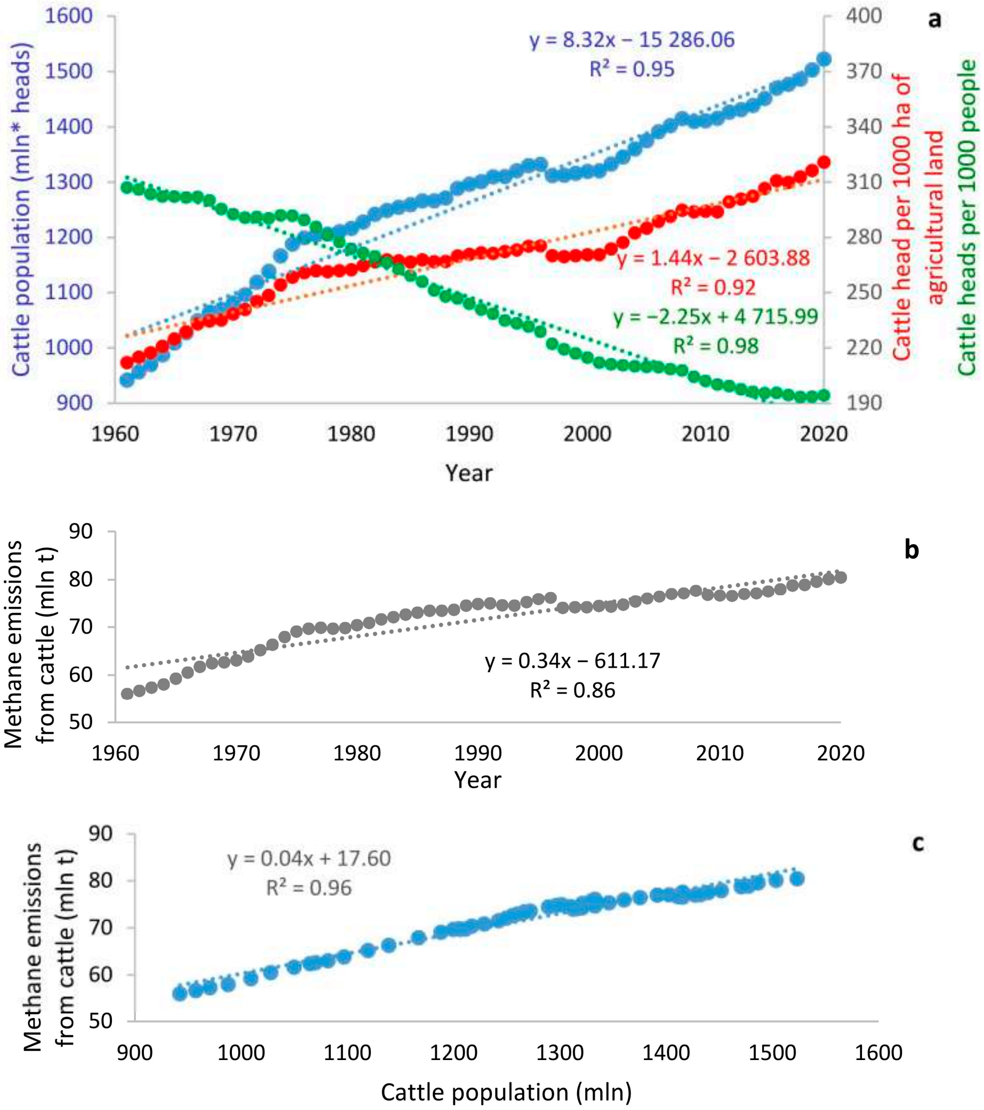

Figure 2. The cattle population (in blue) for the entire world from 1961 to 2020 along with the cattle rate per 1000 ha of agricultural land (in red) and per 1000 people (in green) (**a**), the global CH_4 emission from cattle (in grey), which includes both emissions from enteric fermentation and manure management (**b**) and relationship between the world cattle population and methane emission from cattle (**c**). * mln—million.

Table 2. The mean cattle population for studied countries during the periods 1961–1970 and 2011–2020, as well as the corresponding changes. The color of the background indicates differences between countries in the values shown in the columns.

Country	Cattle (mln * heads)			Cattle Density (heads/1000 ha of Agricultural Land)			Cattle Heads per 1000 People		
	1961–1970	2011–2020	Change **	1961–1970	2011–2020	Change	1961–1970	2011–2020	Change
Argentina	46.3	52.4	13%	351	451	29%	2497	1347	−46%
Australia	19.0	26.9	41%	39	73	88%	2082	1331	−36%
Burkina Faso	2.2	9.4	326%	269	773	188%	494	684	39%
Bangladesh	23.0	23.7	3%	2392	2505	5%	521	171	−67%
Bolivia	2.1	9.1	345%	68	243	255%	614	982	60%
Brazil	65.2	214.4	229%	376	911	142%	1052	1155	10%
Canada	11.5	11.8	2%	182	203	12%	738	367	−50%
Chad	4.4	25.8	488%	92	516	462%	1607	2632	64%
China	52.6	63.1	20%	147	120	−19%	88	49	−45%
Colombia	17.5	24.5	40%	415	532	28%	1310	585	−55%
Germany	18.4	12.3	−33%	948	735	−22%	257	151	−41%
France	20.7	18.9	−9%	614	657	7%	477	313	−34%
Indonesia	6.7	15.7	135%	174	264	52%	87	69	−20%
India	175.9	190.7	8%	993	1063	7%	445	167	−63%
Kenya	7.6	19.9	162%	301	718	139%	1162	560	−52%
Mexico	19.6	33.7	72%	200	343	71%	630	323	−49%
Mali	4.5	10.7	137%	143	260	82%	909	824	−9%
Myanmar	6.1	14.0	128%	575	1091	90%	316	294	−7%
Niger	4.0	12.6	216%	126	274	118%	1339	919	−31%
Nigeria	7.4	19.9	169%	128	290	127%	183	143	−22%
New Zealand	7.4	10.1	37%	467	941	102%	3484	2480	−29%
Pakistan	14.4	42.2	194%	394	1159	194%	352	245	−30%
Paraguay	4.4	13.7	212%	404	820	103%	2623	2517	−4%
Turkey	13.1	14.7	12%	350	385	10%	554	216	−61%
Tanzania	9.2	26.3	185%	343	683	99%	1067	674	−37%
Uganda	3.6	13.8	279%	377	960	155%	558	501	−10%
Uruguay	8.6	11.6	35%	539	814	51%	3649	3506	−4%
United States of America	106.9	92.0	−14%	244	227	−7%	668	311	−53%
Venezuela	7.3	16.2	122%	373	755	102%	1100	615	−44%
South Africa	11.7	13.3	14%	120	138	15%	807	272	−66%

* mln—milion, ** Relative change between two periods, 2011–2020 and 1961–1970 (reference period).

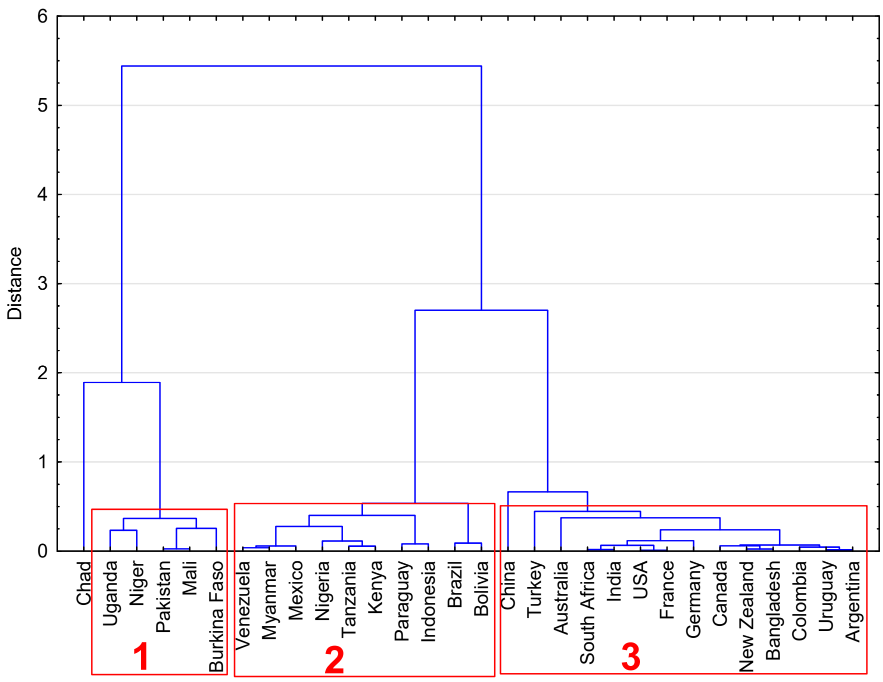

Figure 3. Cluster analysis of trends in cattle population for countries around the world based on relative values of changes for subsequent decades (1961–1970, . . . , 2011–2020).

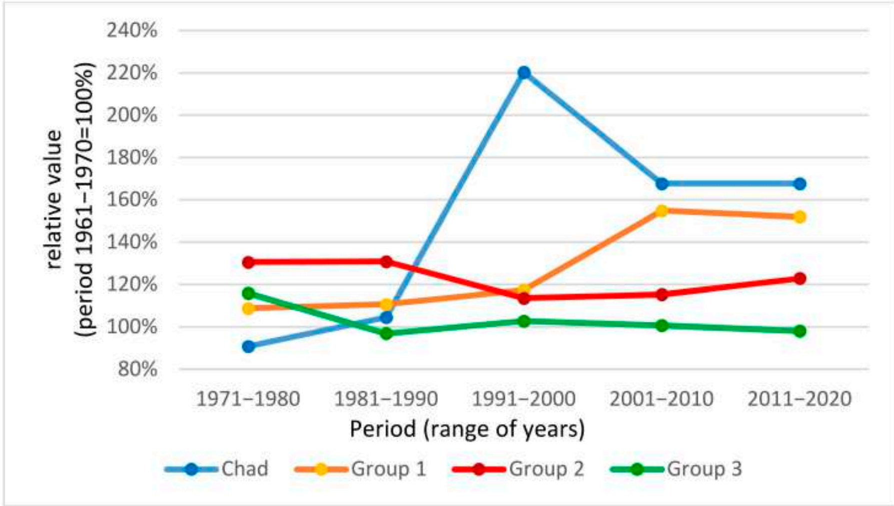

Figure 4. Means values of relative changes in cattle population for subsequent decades (1971–1980, . . . , 2011–2020) compared to the previous decade for groups distinguished by cluster analysis (group of countries are presented in Figure 3).

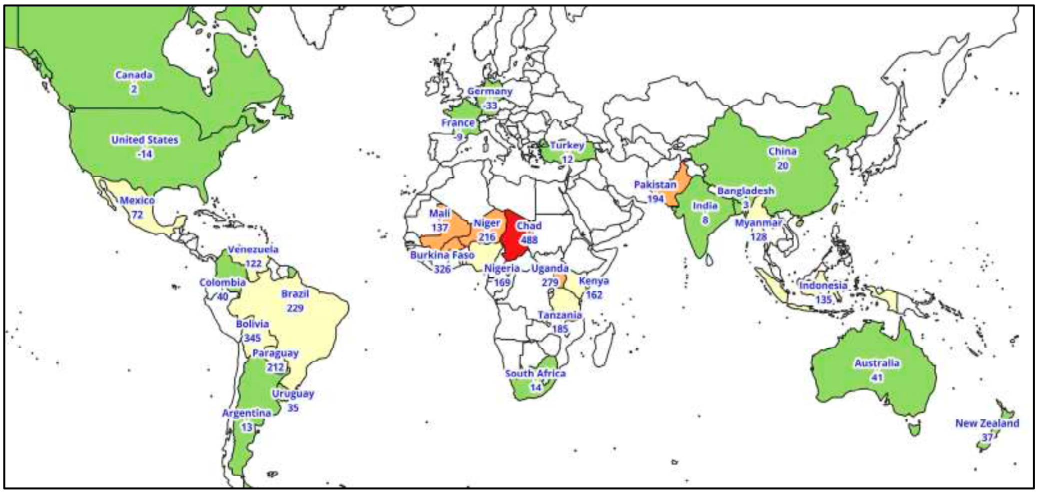

Figure 5. Maps presenting the distinguished groups of countries based on cluster analysis (Figure 3) in different colors: orange for group 1, where a strong increase in cattle population was observed; yellow for group 2, where a strong increase was observed in the first half of the study period followed by a slight increase; green for group 3, where the cattle population remained quite stable along the study period; and Chad in red, indicating a very strong increase. The values next to the country names represent the percentage change in cattle population between 1961–1970 and 2011–2020.

The third group of countries was the largest and included the following countries: Argentina, Uruguay, Colombia (South America), Canada, USA (North America), Germany, France (Europe), Bangladesh, China, India, Turkey (Asia), South Africa, New Zealand and Australia. These countries exhibited a significant increase in cattle population at the beginning of the study period, but from 1981 to 2020, the cattle population remained relatively stable or slightly decreased. The countries in this group are located in different regions of the world, with many of them being highly developed countries.

3.2. Relationship between Cattle Population and Other Variables

To evaluate the relationship between cattle population in each country and various variables that characterize agricultural production, food consumption and economic conditions, a correlation analysis was conducted using yearly data from 1961 to 2020. The results of the correlation analysis are presented in Table 3.

Table 3. Correlation coefficients between cattle population and other variables from 1961 to 2020, categorized by country groups based on cluster analysis. Positive correlations are indicated by red cells, while negative correlations are marked in blue.

Country	Group	AL [1]	FM	GDP	LMP	MBC	MTC	MC	MYA	RPP	TP	CH_4
Chad	0	0.98 *	−0.13	0.75 *	0.00	0.85 *	0.89 *	−0.72 *	−0.80 *	−0.75 *	0.98 *	1.00 *
Burkina Faso	1	0.98 *	0.44 *	0.98 *	0.00	0.76 *	0.85 *	0.03	−0.70 *	−0.95 *	0.98 *	1.00 *
Mali	1	0.85 *	−0.24	0.87 *	0.82 *	0.43 *	0.28 *	0.31 *	−0.84 *	−0.86 *	0.95 *	1.00 *
Niger	1	0.91 *	−0.02	−0.29 *	0.88 *	−0.33 *	−0.49 *	−0.41 *	0.80 *	−0.53 *	0.92 *	1.00 *
Pakistan	1	0.02	0.92 *	0.91 *	0.00	0.97 *	0.87 *	0.06	0.92 *	−0.89 *	0.96 *	1.00 *
Bolivia	2	0.94 *	0.50 *	0.83 *	0.81 *	0.92 *	0.95 *	0.79 *	0.94 *	−0.97 *	0.98 *	1.00 *
Brazil	2	0.78 *	0.93 *	0.96 *	0.66 *	0.97 *	0.96 *	0.95 *	0.79 *	−0.99 *	0.99 *	1.00 *
Indonesia	2	0.92 *	0.94 *	0.96 *	−0.74 *	0.82 *	0.96 *	0.25	0.91 *	−0.94 *	0.94 *	1.00 *
Kenya	2	0.87 *	0.81 *	0.88 *	0.00	−0.36 *	−0.18	0.37 *	0.74 *	−0.88 *	0.92 *	0.98 *
Mexico	2	0.47 *	0.92 *	0.94 *	0.04	0.80 *	0.87 *	0.61 *	0.78 *	−0.94 *	0.88 *	1.00 *
Myanmar	2	0.73 *	0.79 *	0.74 *	−0.24	0.57 *	0.78 *	0.65 *	0.90 *	−0.78 *	0.90 *	0.85 *
Nigeria	2	0.71 *	0.64 *	0.57 *	0.23	−0.62 *	0.50 *	−0.36 *	0.17	−0.97 *	0.95 *	1.00 *
Paraguay	2	0.97 *	0.77 *	0.96 *	0.82 *	−0.68 *	−0.45 *	0.72 *	0.80 *	−0.96 *	0.98 *	1.00 *
Tanzania	2	0.94 *	−0.46 *	0.97 *	0.82 *	−0.19	−0.50 *	0.15	0.96 *	−0.86 *	0.97 *	1.00 *
Uganda	2	0.87 *	0.69 *	0.96 *	0.93 *	−0.38 *	0.33 *	0.79 *	0.53 *	−0.44 *	0.93 *	1.00 *
Venezuela	2	0.87 *	0.93 *	0.57 *	0.93 *	0.15	0.75 *	−0.15	0.05	−0.98 *	0.95 *	1.00 *
Argentina	3	−0.34 *	0.05	0.32 *	−0.39 *	−0.10	0.11	0.12	0.15	−0.42 *	0.31 *	1.00 *
Australia	3	−0.28 *	0.50 *	0.49 *	−0.28	0.14	0.59 *	−0.56 *	0.43 *	−0.56 *	0.46 *	0.99 *
Bangladesh	3	0.27 *	−0.04	−0.05	0.00	0.34 *	0.01	−0.09	0.45 *	0.17	−0.13	0.94 *
Canada	3	0.10	−0.10	−0.53 *	0.03	0.04	0.51 *	−0.05	0.25	−0.26 *	0.25	0.40 *
China	3	0.71 *	0.38 *	0.10	0.71 *	0.47 *	0.47 *	0.25	0.23	−0.24	0.56 *	0.99 *
Colombia	3	0.44 *	0.39 *	0.67 *	0.61 *	−0.38 *	0.53 *	0.39 *	0.36 *	−0.85 *	0.72 *	0.99 *
France	3	0.52 *	0.77 *	−0.54 *	0.71 *	0.80 *	0.04	0.53 *	−0.69 *	0.31 *	−0.54 *	0.95 *
Germany	3	0.79 *	0.97 *	−0.91 *	0.78 *	0.94 *	0.13	−0.05	−0.88 *	0.69 *	−0.59 *	0.99 *
India	3	0.81 *	0.33 *	0.32 *	−0.72 *	−0.16	0.51 *	0.69 *	0.43 *	−0.63 *	0.54 *	0.85 *
New Zealand	3	−0.80 *	0.81 *	0.93 *	−0.70 *	−0.57 *	−0.04	−0.51 *	0.81 *	−0.77 *	0.85 *	0.96 *
South Africa	3	0.21	−0.57 *	0.30 *	0.07	−0.35 *	0.42 *	−0.63 *	0.54 *	−0.61 *	0.64 *	1.00 *
Turkey	3	−0.65 *	−0.18	0.12	−0.32 *	0.30 *	0.10	0.75 *	0.08	0.12	−0.07	0.98 *
Uruguay	3	−0.75 *	0.19	0.74 *	−0.64 *	−0.73 *	−0.68 *	0.09	0.71 *	−0.80 *	0.82 *	1.00 *
USA	3	0.67 *	0.24	−0.75 *	−0.05	0.92 *	−0.58 *	0.27 *	−0.75 *	0.60 *	−0.72 *	0.94 *

* Significant correlations at 0.05 probability level. [1] Abbreviations used in the table: agricultural land (AL), farm machinery (FM), gross domestic product per capita (GDP), land under perm. meadows and pastures (LMP), meat beef consumption per capita (MBC), meat total (incl. fish and seafood) consumption per capita (MTC), milk consumption per capita (MC), milk yield per animal (MYA), rural population percent (RPP), total population (TP), methane emission from cattle enteric fermentation and manure management (CH_4).

For all countries from the first and second groups, as well as Chad, a very strong positive correlation was observed between the cattle population and the human population. The correlation coefficients ranged from 0.85 to 0.99, indicating that the increase in cattle population in these countries was almost linearly associated with the growth of the human population. Moreover, cattle population showed a strong positive correlation with GDP per capita and the area of agricultural land while exhibiting a negative correlation with the percentage of rural population. These significant correlations were observed for most countries from the first and second groups, although not for all of them. Other correlations within the first and second groups were less consistent. For example, an increase in cattle population was associated with an increase in milk yield per animal, but only for approximately two-thirds of the countries in these groups.

The correlations within the third group of countries were not consistent, as both negative and positive correlations with cattle populations were observed for all variables. Most of these correlations were weaker compared to those observed in countries belonging to the first and second groups.

For Canada, the correlation coefficient between changes in cattle population and changes in CH_4 emissions from cattle is positive and statistically significant, albeit lower compared to other countries. This is because the population of dairy cattle in Canada has been declining over the study period, while the number of non-dairy cattle has increased or fluctuated. Dairy cattle tend to have higher CH_4 emission factors compared to beef cattle (Table 1), which explains the weaker correlation between cattle population and CH_4 emission from cattle during the study period.

In addition to calculating correlations for each country, correlations were also calculated across all countries based on the means for the period 2011–2020. These correlations encompassed all the studied variables. In addition, two ratios: cattle-to-agricultural land and cattle-to-total human population, were included in the analysis. The results showed that the cattle population was significantly correlated only with the area of agricultural land and the total human population. These correlations were positive, indicating that larger agricultural areas are necessary to support a larger population of cattle, and a larger human population may require more animal-based food. The ratio of cattle-to-agricultural land was found to be significantly correlated with both the area of agricultural land and the area of land under permanent meadows and pastures. The correlation was negative, suggesting that countries with larger agricultural areas, including meadows and pastures, tend to have a lower cattle density per unit area. Additionally, the ratio of cattle-to-total-human population exhibited a significant correlation with beef consumption per capita. The correlation was positive, indicating that countries with higher beef consumption tend to have a higher cattle population per 1000 people. However, there was no significant correlation found with milk consumption. These relationships, as presented in Table 4, are also visualized in the form of a PCA biplot in Figure 6.

Table 4. The correlation coefficients between all studied variables in all countries based on the means for 2011–2020.

	CT	CT/AL	CT/TP	AL	FM	GDP	LMP	MBC	MTC	MC	MYA	RPP	TP	CH_4
Cattle population (CT)		0.13	−0.11	0.50 *	0.14	0.00	0.33	0.21	0.11	0.16	0.05	−0.09	0.57 *	0.96 *
Cattle/agricultural land (CT/AL)	0.13		0.03	−0.37	−0.07	−0.26	−0.41 *	−0.27	−0.30	−0.17	−0.34	0.27	−0.02	0.07
Cattle/total population (CT/TP)	−0.11	0.03		−0.16	−0.21	0.07	−0.06	0.46 *	0.11	0.19	−0.06	−0.25	−0.32	−0.07
Agricultural land (AL)	0.50 *	−0.37	−0.16		0.56 *	0.38 *	0.96 *	0.28	0.48 *	0.25	0.36 *	−0.19	0.65 *	0.56 *
Farm machinery (FM)	0.14	−0.07	−0.21	0.56 *		0.21	0.52 *	−0.10	0.31	0.08	0.24	−0.10	0.70 *	0.16
GDP per capita (GDP)	0.00	−0.26	0.07	0.38 *	0.21		0.40 *	0.56 *	0.79 *	0.80 *	0.88 *	−0.66 *	−0.08	0.13
Land under perm. meadows and pastures (LMP)	0.33	−0.41	−0.06	0.96 *	0.52	0.40 *		0.34	0.54 *	0.27	0.33	−0.24	0.47 *	0.43 *
Meat beef consumption per capita (MBC)	0.21	−0.27	0.46	0.28	−0.10	0.56 *	0.34		0.73 *	0.74 *	0.62 *	−0.75 *	−0.27	0.36 *
Meat total (incl. fish and seafood) consumption per capita (MTC)	0.11	−0.30	0.11	0.48 *	0.31	0.79 *	0.54 *	0.73 *		0.68 *	0.79 *	−0.74 *	−0.02	0.29
Milk consumption per capita (MC)	0.16	−0.17	0.19	0.25	0.08	0.80 *	0.27	0.74 *	0.68 *		0.78 *	−0.81 *	−0.16	0.29
Milk yield per animal (MYA)	0.05	−0.34	−0.06	0.36 *	0.24	0.88 *	0.33	0.62 *	0.79 *	0.78 *		−0.70 *	0.00	0.18
Rural population percent (RPP)	−0.09	0.27	−0.25	−0.19	−0.10	−0.66 *	−0.24	−0.75 *	−0.74 *	−0.81 *	−0.70 *		0.17	−0.23
Total population (TP)	0.57 *	−0.02	−0.32	0.65 *	0.70	−0.08	0.47 *	−0.27	−0.02	−0.16	0.00	0.17		0.46 *
Methane emission (CH_4)	0.96 *	0.07	−0.07	0.56 *	0.16	0.13	0.43 *	0.36 *	0.29	0.29	0.18	−0.23	0.46 *	

* Significant correlations at 0.05 probability level.

Positive correlations can be observed across countries for the following variables: GDP per capita (GDP), land under perm. meadows and pastures (LMP), meat beef consumption per capita (MBC), meat total (incl. fish and seafood) consumption per capita (MTC), milk consumption per capita (MC), milk yield per animal (MYA). Conversely, these variables exhibit negative correlations with the percentage of rural population (RPP). Therefore, countries with higher GDP per capita tend to have higher meat and milk consumption per capita, higher milk yield per animal, and a lower percentage of rural population. These are the United States, Australia, Argentina, France, Canada, Brazil, Germany and New Zealand (located on the left side of the biplot in Figure 6). On the other hand, countries like Bangladesh, Uganda, Burkina Faso, Niger, Tanzania, Nigeria and Kenya (located on the right side of the biplot in Figure 6) exhibit lower meat and milk consumption per capita, lower milk yield per animal, and a higher percentage of rural population. Strong positive correlations were identified between cattle population (CP) and farm machinery (FM), methane emission attributed to cattle (CH_4), agricultural land (AL), land under perm. meadows and pastures (LMP). Notably, Brazil stands out as the country with the highest values for these variables.

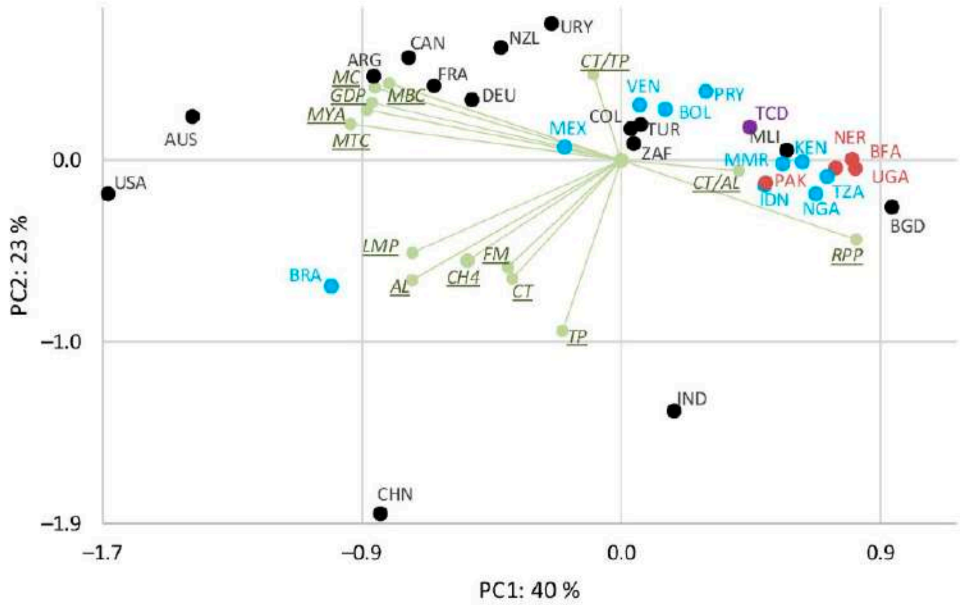

Figure 6. PCA biplot illustrating the relationships between the studied variables, as well as the multivariate differences among the countries included in the analysis, based on the means for the period 2011–2020. Abbreviations variables (marked in green and underlined): the size of the cattle population (CT) in the country and other variables which can be related to the cattle population: agricultural land (AL), farm machinery (FM), GDP per capita (GDP), land under perm. meadows and pastures (LMP), beef consumption per capita (MBC), meat total (incl. fish and seafood) consumption per capita (MTC), milk consumption per capita (MC), milk yield per animal (MYA), rural population percent (RPP), total population (TP) and two ratios based on cattle population, cattle/agricultural land (CT/AL), cattle/total population (CT/TP), methane emission connected with cattle (CH_4); countries: Argentina (ARG), Australia (AUS), Bolivia (BOL), Brazil (BRA), Burkina Faso (BFA), Canada (CAN), Chad (TCD), China (CHN), Colombia (COL), France (FRA), Germany (DEU), India (IND), Indonesia (IDN), Kenya (KEN), Mali (MLI), Mexico (MEX), Myanmar (MMR), New Zealand (NZL), Niger (NER), Nigeria (NGA), Paraguay (PRY), South Africa (ZAF), Turkey (TUR), Uganda (UGA), United Republic of Tanzania (TZA), the United States of America (USA), Uruguay (URY), Venezuela (VEN). Different colors of dots for countries indicate groups distinguished in cluster analysis (Figure 3).

4. Discussion

This study focused on examining the contribution of livestock systems to global warming by analyzing the emissions directly and unambiguously attributed to livestock. The analysis found a strong correlation between cattle population and CH_4 emission from cattle, with a correlation coefficient of 0.96 across countries for the last decade (2011–2020). The temporal pattern of changes in cattle population and CH_4 emissions at a global scale exhibited a similar trend.

These CH_4 emission estimations are based on Tier 1 factors, which are less detailed and may introduce biases. These factors consider regional differences in production intensity and categorize cattle into dairy and non-dairy types. To obtain more accurate emission factors, the Tier 2 method is used, which takes into account specific characteristics and activities of different livestock groups [2]. This approach considers factors like animal characteristics, diet, housing conditions, manure management practices, and other relevant parameters. By incorporating these factors, Tier 2 provides a more precise estimation of greenhouse gas emissions compared to default values. Calculating emission factors using the Tier 2 method requires detailed activity data specific to livestock categories. This data includes information on animal numbers, production parameters, feed consumption, manure management practices and other factors that influence emissions. Studies on CH_4 emissions from enteric fermentation and manure management have shown variations in emission factor values, typically around 20%. For example, the UNFCCC (the United Nations Framework Convention on Climate Change) inventory reports indicate that the US reported an enteric fermentation CH_4 emission factor for dairy cows of 121 kg CH_4 head^{-1} in 1990 and 149 kg CH_4 head^{-1} in 2020. However, FAOSTAT uses a value of 128 for dairy cows in the US. Similar variations exist in the case of manure management. Notably, CH_4 emission rates for manure management can be significantly lower than those for enteric fermentation. The structure of cattle populations and rearing methods also influence CH_4 emissions. Although presented study did not account for this structure due to data limitations, its main objective was to demonstrate global trends in cattle population changes and their implications, such as CH_4 emissions from livestock.

Presented findings revealed different patterns of temporal changes in cattle populations among groups of countries. Two groups exhibited a strong correlation between cattle and human population growth, mainly in developing or middle-income countries located in Africa, South America, and Southeastern Asia. These countries showed a substantial increase in both cattle and human populations, along with a rise in milk and meat consumption [24,25]. However, their milk and meat consumption levels still remain lower than those in developed countries. The third group consisted primarily of highly developed countries, where cattle populations remained relatively stable, and an increase in cattle production efficiency was observed.

Over the study period (1961–2020), the global human population increased by approximately 155%, from 3.07 to 7.84 billion people, while the cattle population increased by about 62% [26]. This raises the question of whether increasing the cattle population is necessary to meet the growing food demands. It is possible to produce more beef and milk with the same cattle population by enhancing production efficiency. A notable example is the US, where the human population increased by over 100% during the same period, yet the cattle population either remained stable or slightly decreased. Such improvements in cattle production efficiency are beneficial for reducing CH_4 emissions as they decrease the emissions per unit of protein produced [16,27]. In many developing countries, CH_4 emissions per unit of production are still very high, and there is high potential for increased intensity of beef and milk production to reduce CH_4 emissions. Developing countries, especially those in Southeastern Asia and sub-Saharan Africa, still have high CH_4 emissions per unit of production, suggesting significant potential for emission intensity reduction through increased efficiency [16]. Productivity gains are particularly crucial for regions experiencing high population growth, as is the case for many developing countries.

In tropical climates, where many developing countries are located, the same livestock management practices used in developed countries may not be applicable. However, one potential approach to reduce CH_4 emissions during cattle production in tropical climates is through crossbreeding, which has the potential to improve performance [28]. A study by Haas et al. [29] demonstrated that genetic progress can reduce the intensity of CH_4 emissions (CH_4 emitted per kg of milk) by approximately 20% over the next 30 years in European conditions.

One challenge associated with improving cattle production efficiency is the negative effect of heat stress, particularly on dairy cows, leading to decreased milk production [30]. Heat stress also diminishes the efficiency of meat production [31,32]. Unfortunately, continuous climate warming exacerbates heat stress in cattle production, posing a significant obstacle to increasing production efficiency, especially in tropical climates.

Various methods can be employed to mitigate global warming by reducing CH_4 emissions in cattle production. These methods include improved grazing management, dietary modifications and nutrition for livestock, genetic improvement, better manure management [10,33]. A simple strategy for cattle producers to reduce CH_4 emissions is to adopt the practices currently used by leading producers with the lowest emission intensity. While most studies on CH_4 reduction in cattle focus on changes in enteric emissions but efforts should encompass a more comprehensive approach that includes other GHG emissions associated with cattle production [34].

Changes in livestock CH_4 emissions were primarily influenced by shifts in human population dynamics. However, in highly developed countries, emissions have been reduced through increased efficiency in cattle production. The current global challenges related to increased CH_4 emissions from cattle production are primarily concentrated in developing countries, where cattle production efficiency remains low despite growing demands for food due to population growth [35,36]. Our study, along with other research [35], has identified an ongoing increase in CH_4 emissions in regions like South Asia, tropical Africa and Brazil, driven by the expansion of cattle populations and low production efficiency. Highly developed countries still have the potential to reduce CH_4 emission from cattle production, although this potential is comparatively lower than that of developing countries, mainly due to stable human populations [37,38].

5. Conclusions

During the period from 1961 to 2020, the increase in human population was the primary driver behind the rise in cattle population in less developed countries, predominantly located in Africa and South America. Conversely, developed countries experienced relatively stable cattle populations, but notable improvements in cattle production efficiency were observed, such as higher milk yield per animal. Since methane emission is strongly correlated with cattle population, there is significant potential for mitigating CH_4 emissions from cattle production, particularly in developing countries. These regions offer favorable conditions for introducing more efficient cattle management, which can lead to higher beef and milk production while maintaining a similar cattle population.

In planning for future changes in milk and beef production, it is crucial to prioritize achieving higher production efficiency. This can be accomplished by increasing production intensity while ensuring the well-being of the animals. By focusing on both efficiency and animal welfare, it is possible to meet the growing demands for milk and beef while minimizing the environmental impact associated with methane emissions.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kozicka, K., Žukovskis, J., Wójcik-Gront, E. 2023. Explaining global trends in cattle population changes between 1961 and 2020 directly affecting methane emissions. *Sustainability* 15(13):10533, mój indywidualny udział w jej powstaniu polegał na opracowaniu założeń metodycznych, przetwarzaniu danych oraz przygotowaniu oryginalnego tekstu pracy. Udział procentowy szacuję na 65%.

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Podpis

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NOTE

Spatial distribution of CH_4 emissions from livestock farming in Poland: a comparison of 2010 and 2020

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ABSTRACT

Among greenhouse gases (GHGs), methane (CH_4) is a major contributor to global warming. Agriculture accounts for about 40% of CH_4 emissions, with livestock being a crucial source. CH_4 emissions from livestock primarily arise during enteric fermentation and manure management in livestock. This study aims to estimate Poland's CH_4 emissions from enteric fermentation and manure management in 2010 and 2020 at the municipal level (LAU-2). Data from the National Agricultural Census (NAC) and the UNFCCC National Inventory Report (NIR) for 2010 and 2020 were used for the analysis. The results reveal a slight overall increase in total CH_4 emissions from livestock farming in Poland over the decade. The highest emissions were observed in regions where livestock farming was predominant, while significant changes in emissions occurred in regions experiencing considerable livestock production growth. Conversely, the lowest emissions were found in areas where the decrease in livestock population was most prominent. Understanding the spatial distribution of CH_4 emissions from livestock farming at the municipal level is essential for effective climate change mitigation efforts. This study highlights the importance of continuous monitoring and analysis of livestock farming in Poland to assess its impact on GHG emissions and facilitate informed policy-making for sustainable agricultural practices.

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Spatial distribution; methane; agriculture; livestock; IPCC

Introduction

The main greenhouse gases (GHG) include carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (N_2O). Their global warming potential (GWP) depends on their ability to absorb solar radiation and the time they remain in the atmosphere, measured in CO_2 equivalent (Suttie, 2008). CH_4 has a GWP estimated to be 27–30 times greater than CO_2 over a 100-year time frame (Us Epa, 2022), making it a significant contributor to climate change. Anthropogenic sources, particularly agriculture, contribute to about 40% of CH_4 emissions (Ritchie et al., 2020), with livestock being crucial. CH_4 emissions from livestock arise during enteric fermentation, primarily from ruminant animals, and to a lesser extent from monogastric animals (Albrektsen et al., 2021). The rumen's digestion and fermentation of feed by microorganisms produce CH_4 gas, with approximately 95% of it released through belching and the remaining 5% through the rectum (Ramin et al., 2020). CH_4 emissions from enteric fermentation depend on factors such as feed type, quality, digestibility, and intake amount (Johnson & Johnson, 1995). Additionally, manure management contributes to CH_4 emissions, but to a lesser extent (Yusuf et al., 2012). When manure is stored in liquid systems, CH_4 is produced under anaerobic conditions (Dalby et al., 2021), and extending the storage time at favourable temperatures increases both the rate and duration of CH_4 emissions (Philippe et al., 2007; Steed & Hashimoto, 1994).

Estimation of CH_4 emissions

Estimating local GHG emissions often involves using the Intergovernmental Panel on Climate Change (IPCC) guidelines, enabling reporting to the United Nations Framework Convention on Climate Change (UNFCCC) inventories. Estimating CH_4 emissions from livestock husbandry requires defining animal categories and subcategories, annual population data, and, in more complex scenarios (Tiers), detailed country-specific information on gross energy intake and CH_4 conversion factor (Ym) for each livestock category (Eggleston et al., 2006). When estimating CH_4 emissions from enteric fermentation, classification by type of digestive system is crucial, with ruminants (cattle, buffalo, goats, sheep, deer, and camelids) producing more CH_4 than non-ruminants (pigs, horses, mules, and asses), where methanogenic

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fermentation occurs mainly in the last third of the small intestine (Jørgensen et al., 2011). Feed intake also significantly affects CH_4 production, as higher intake leads to increased gas emissions (Ulyatt & Lassey, 2001). Feed intake is influenced by the animal's size, growth rate, and production characteristics, such as milk production, wool growth, or pregnancy. Regarding CH_4 emissions from manure management, the amount of produced manure plays a critical role and is influenced by the animal population and the rate of waste production. Additionally, the manure storage system affects CH_4 emissions, with anaerobic conditions leading to higher emissions. Conversely, treating waste as solid (e.g. in piles or pits) or storing it in pastures or agricultural fields results in lower CH_4 production (Montes et al., 2013).

Poland, as a signatory to the UNFCCC, is obligated to prepare annual inventory reports. In the agricultural sector, CH_4 emissions arise from enteric fermentation and manure management. The animal category is divided into cattle (including dairy cows and non-dairy cattle), sheep, swine, and non-dairy (including goats, horses, and poultry). CH_4 emissions (in kilotons – kt) are calculated using the IPCC 2006 methodology based on the animal category's population size (in thousands) and the CH_4 emission factor (EF) (in kg CH_4/head/yr). The EF for enteric fermentation is computed using the formula (Eggleston et al., 2006):

$$EF = \left[\frac{GE * \left(\frac{Y_m}{100}\right) * 365}{55.65} \right]$$

where:

EF – emission factor (kg CH_4/head/year);
GE – gross energy intake (MJ/head/day), based on body weight, milk production, net energy (NE), digestible energy (DE);
Y_m – CH_4 conversion rate, the percent of gross energy in feed converted to CH_4 (%);
Factor 55.65 MJ/kg CH_4 – energy content of CH_4.

For manure management, the CH_4 EF is estimated based on the daily volatile solid excreted (VS) for the livestock category, the maximum CH_4-producing capacity for manure produced by an animal, and the CH_4 conversion factor (MCF) for each manure management system suitable for a cool climate, considering liquid systems, solid storage, and pasture information (Poland's National Inventory Report, 2022; Wójcik-Gront & Ollik, 2018). According to Poland's National Inventory Report (NIR) 2020, CH_4 emissions from enteric fermentation decreased by 35.6% and from manure management by 43% between 1988 and 2020.

Table 1. Livestock population (in thousands) in 2010 and 2020 (based on National Agricultural Census, 2020.).

	2010	2020
Cattle	5742	6306
Dairy cows	2646	2475
Swine	15244	11153
Poultry	174326	225636

National agricultural census

For a more detailed analysis of the state of Polish agriculture and the changes that have occurred in this sector, the Central Statistical Office (CSO) provides reports that are based on information collected from farmers at a particular time. The National Agricultural Census (NAC) was published in 2010 and 2020, presenting results on farms, land use, fertilization, and livestock at the national, provincial, and municipal levels. Table 1 presents the comparison of livestock populations in 2010 and 2020. While there was an overall increase of 9.8% in cattle, the dairy cow population decreased by 6.5% due to the elimination of milk limits and fluctuations in milk prices. The swine population also declined by 26.8% due to the low profitability of fattening and the ASF (African Swine Fever) disease. However, the poultry population increased by 29.4% due to poultry sales in foreign markets (National Agricultural Census, 2020).

The analysis of changes in livestock populations and GHG emissions at the national level is crucial for climate change mitigation efforts. Therefore, the study aimed to estimate CH_4 emissions from enteric fermentation and manure management for Poland in 2010 and 2020 at the municipal level (LAU-2). For the study, NAC data on livestock populations (dairy and non-dairy cattle, swine, and poultry) and the UNFCCC National Inventory Report (NIR) CH_4 EF for individual animals in 2010 and 2020 were used. The results obtained for 2010 and 2020 were compared to analyse changes in the CH_4 emissions from livestock for municipalities across Poland. Using data from the National Agricultural Census, the research summarizes CH_4 emissions from enteric fermentation and manure management both in total and at the municipality level, for Poland in 2010 and 2020.

Materials and methods

The study utilized data on livestock populations on individual farms based on NAC 2010 and 2020, obtained from the CSO Local Database. The available data included livestock numbers of dairy and non-dairy cattle, swine, and poultry. For municipalities with a very low number of livestock farms, data were withheld due to statistical secrecy. In these cases, the livestock population was assumed to be 0 to analyse the spatial

Table 2. Livestock EFs (in kg CH_4/head/yr) for Poland in 2010 and 2020 (based on Poland NIR 2022).

	Enteric fermentation		Manure management	
	2010	2020	2010	2020
Dairy cattle	109.29	120.53	8.58	7.84
Non-dairy cattle	50.07	50.57	2.02	1.73
Swine	1.50	1.50	1.68	1.38
Poultry	–	–	0.03	0.03

distribution of emissions. To calculate the total emissions, missing data were supplemented with data from higher territorial units.

CH_4 emissions [Gg CH_4 yr^{-1}] from enteric fermentation and manure management for each municipality in Poland were calculated based on the IPCC methodology, where the CH_4 EF for a specific livestock population was multiplied by the population of animals in that category. CH_4 EFs for each livestock category for 2010 and 2020 (Table 2) were taken from the Poland's NIR (2022). For poultry, the EF was provided only for emissions from manure.

Total CH_4 emissions and the changes that occurred from 2010 to 2020 were then estimated for each municipality (2,472) and voivodship (16), broken down by livestock category. For each of the result the uncertainties of the estimated emissions were determined.

Results and discussion

Total livestock CH_4 emissions

Total CH_4 emissions from livestock farming in Poland increased slightly over the decade amounting to 528 Gg in 2010 and 557 Gg in 2020. The increase in CH_4 emissions between 2010 and 2020 is mainly attributed to the rise in the non-dairy cattle population, partially offset by a decrease in the swine population. Figure 1 presents the comparison of CH_4 emissions from each livestock category in 2010 and 2020. Despite dairy cattle contributing the highest share of total CH_4 emissions (57.2% in 2020), the increase in emissions by 2020 was not significant (1.6%), owing to the decline in the dairy cattle population. Non-dairy cattle total CH_4 emissions increased by 23.4% in 2020, while emissions from swine decreased by 34% in 2020, consistent with the population changes. The share of poultry was negligible – below 1.1%, however, due to an increasing population, the emissions in 2020 were higher by 28.7% than in 2010. The amount of emissions is influenced by various factors, including livestock population and changes in CH_4 EF for each livestock category. According to Poland NIR 2022, cattle EF increased for enteric fermentation in 2020, following the GE changes (Table 2). After joining the EU in 2004, Poland's milk production rapidly increased, influenced by EU standards and the Common Agricultural Policy. The implementation of milk limits has forced smaller producers to either resign or shift to semi-subsistence farming (Kowalska, 2014; Milczarek-Andrzejewska et al., 2008). However, apart from the decreasing trend in the dairy cattle population, the average milk yield improved from 4,487 liters/cow/year in 2010 to 5,946 liters/cow/year in 2020, driven by investments in high-quality feed and barn modernizations (Kowalska et al., 2019). The CH_4 emissions from manure management are generated mainly by cattle (mainly lactating) and swine (Sefeedpari et al., 2020). The amount of emissions again depends on livestock population and EF, with the latter mainly influenced by the amount of VS for the livestock category and MCF for each manure management system. The EFs from manure management for cattle and swine decreased in 2020 (Table 2). The declining trend in CH_4 emissions from manure is related to a dynamic decrease in livestock farms and changes in storage systems (Kopiński & Wrzaszcz, 2020). According to Poland NIR 2022, solid manure management

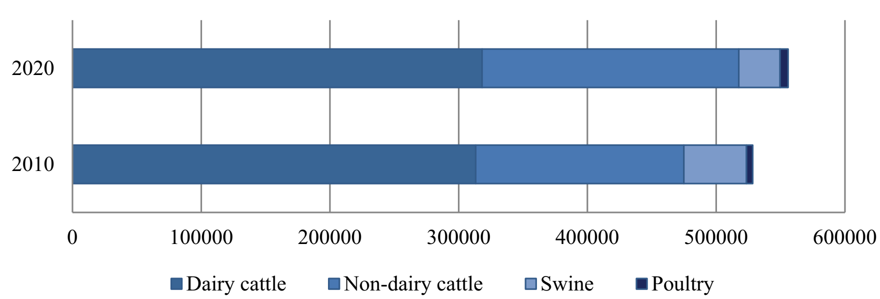

Figure 1. Comparison of livestock CH_4 emissions between 2010 and 2020 (in t).

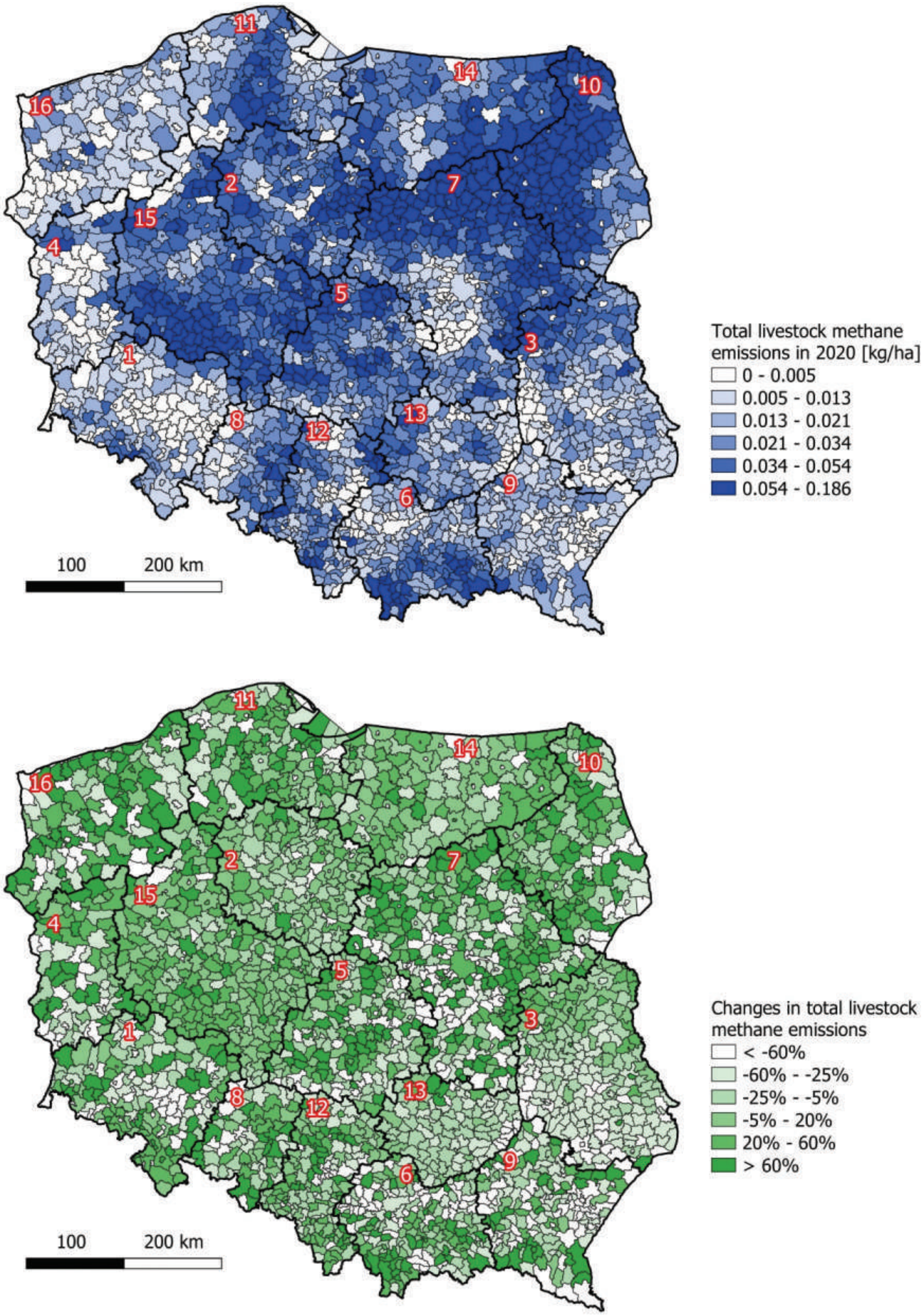

Figure 2. Spatial distribution of total livestock CH_4 emission (kg ha^{-1}) in 2020 and its changes between 2010 and 2020 [%]. Voivodship IDs: 1 - Dolnośląskie; 2 - Kujawsko-Pomorskie; 3 - Lubelskie; 4 - Lubuskie; 5 - Łódzkie; 6 - Małopolskie; 7 - Mazowieckie; 8 - Opolskie; 9 - Podkarpackie; 10 - Podlaskie; 11 - Pomorskie; 12 - Śląskie; 13 - Świętokrzyskie; 14 - warmińsko-Mazurskie; 15 - Wielkopolskie; 16 - Zachodniopomorskie.

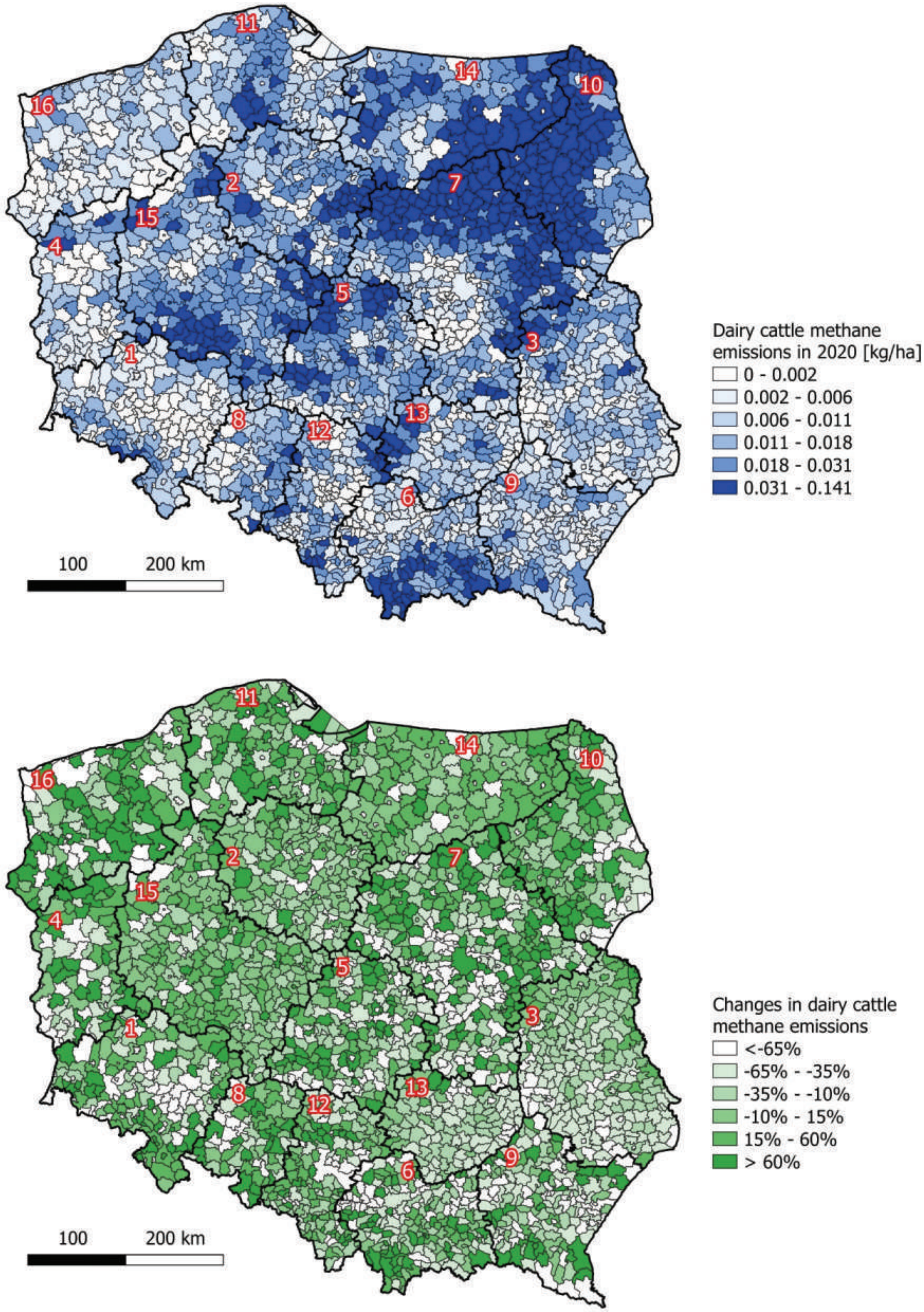

Figure 3. Spatial distribution of dairy cattle CH_4 emissions (kg ha^{-1}) in 2020 and its changes between 2010 and 2020 [%]. Voivodship IDs: 1 - Dolnośląskie; 2 - Kujawsko-Pomorskie; 3 - Lubelskie; 4 - Lubuskie; 5 - Łódzkie; 6 - Małopolskie; 7 - Mazowieckie; 8 - Opolskie; 9 - Podkarpackie; 10 - Podlaskie; 11 - Pomorskie; 12 - Śląskie; 13 - Świętokrzyskie; 14 - warmińsko-Mazurskie; 15 - Wielkopolskie; 16 - Zachodniopomorskie.

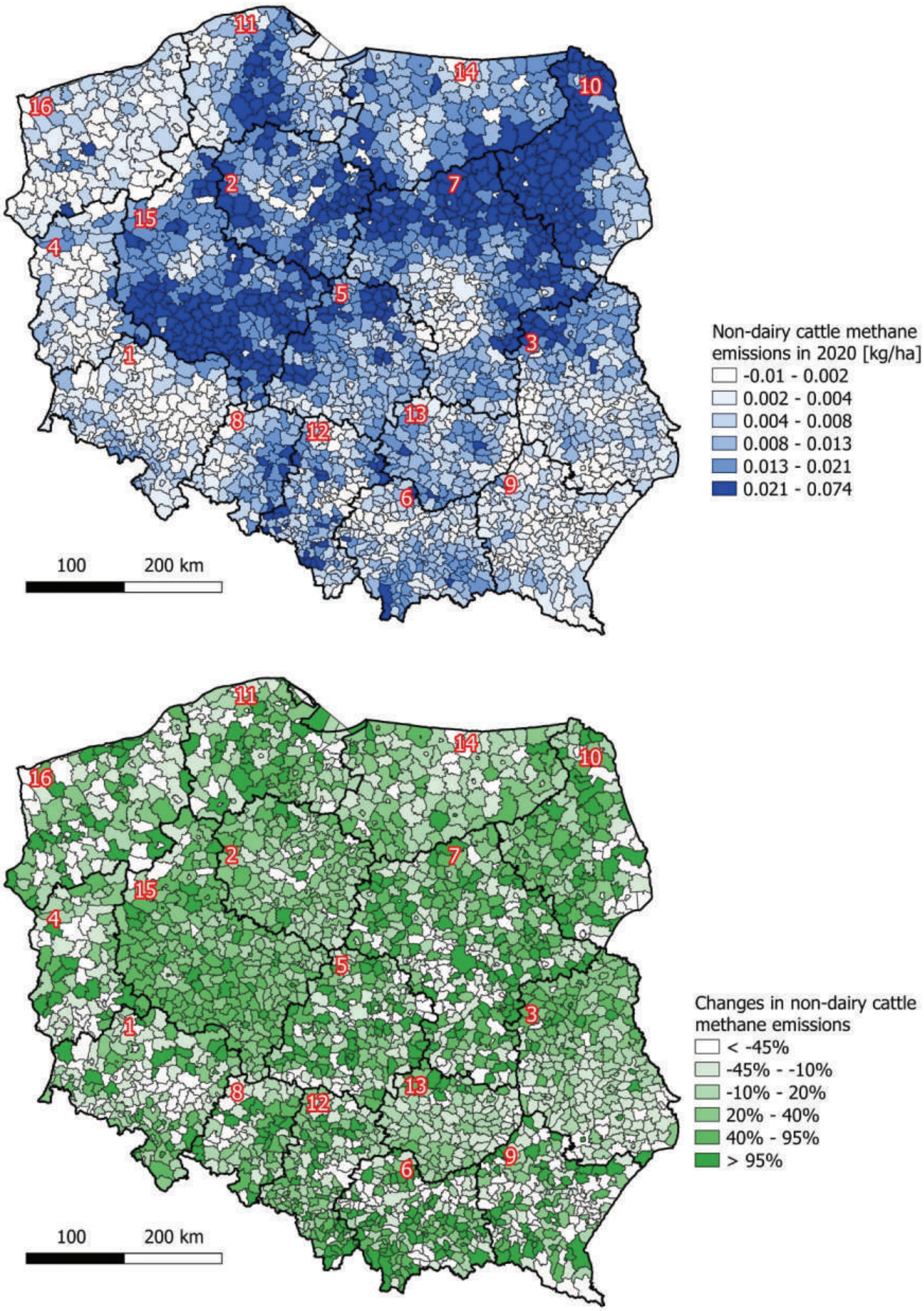

Figure 4. Spatial distribution of non-dairy cattle CH_4 emission (kg ha^{-1}) in 2020 and its changes between 2010 and 2020 [%]. Voivodship IDs: 1 - Dolnośląskie; 2 - Kujawsko-Pomorskie; 3 - Lubelskie; 4 - Lubuskie; 5 - Łódzkie; 6 - Małopolskie; 7 - Mazowieckie; 8 - Opolskie; 9 - Podkarpackie; 10 - Podlaskie; 11 - Pomorskie; 12 - Śląskie; 13 - Świętokrzyskie; 14 - warmińsko-Mazurskie; 15 - Wielkopolskie; 16 - Zachodniopomorskie.

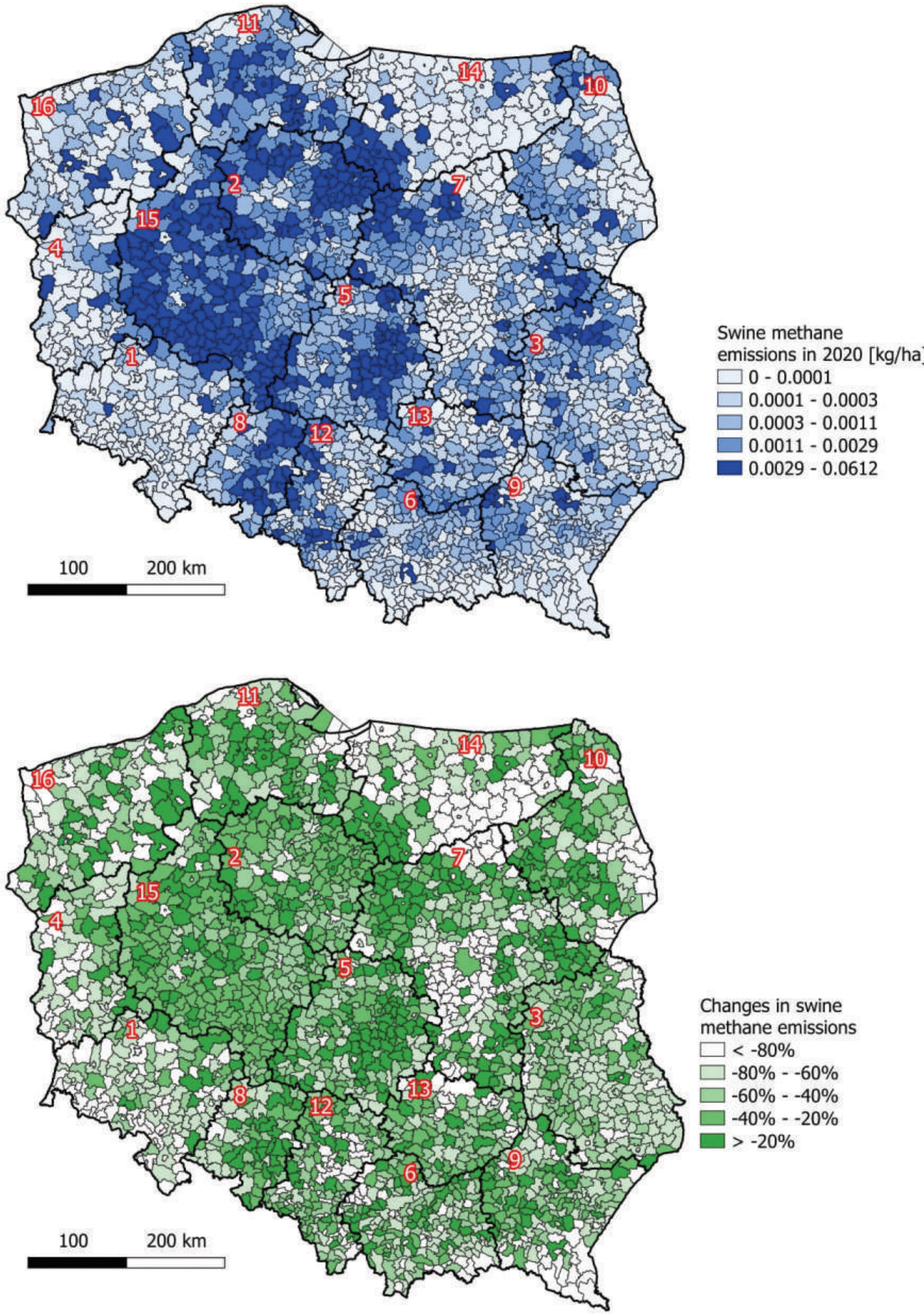

Figure 5. Spatial distribution of swine CH_4 emission (kg ha^{-1}) in 2020 and its changes between 2010 and 2020 [%]. Voivodship IDs: 1 - Dolnośląskie; 2 - Kujawsko-Pomorskie; 3 - Lubelskie; 4 - Lubuskie; 5 - Łódzkie; 6 - Małopolskie; 7 - Mazowieckie; 8 - Opolskie; 9 - Podkarpackie; 10 - Podlaskie; 11 - Pomorskie; 12 - Śląskie; 13 - Świętokrzyskie; 14 - warmińsko-Mazurskie; 15 - Wielkopolskie; 16 - Zachodniopomorskie.

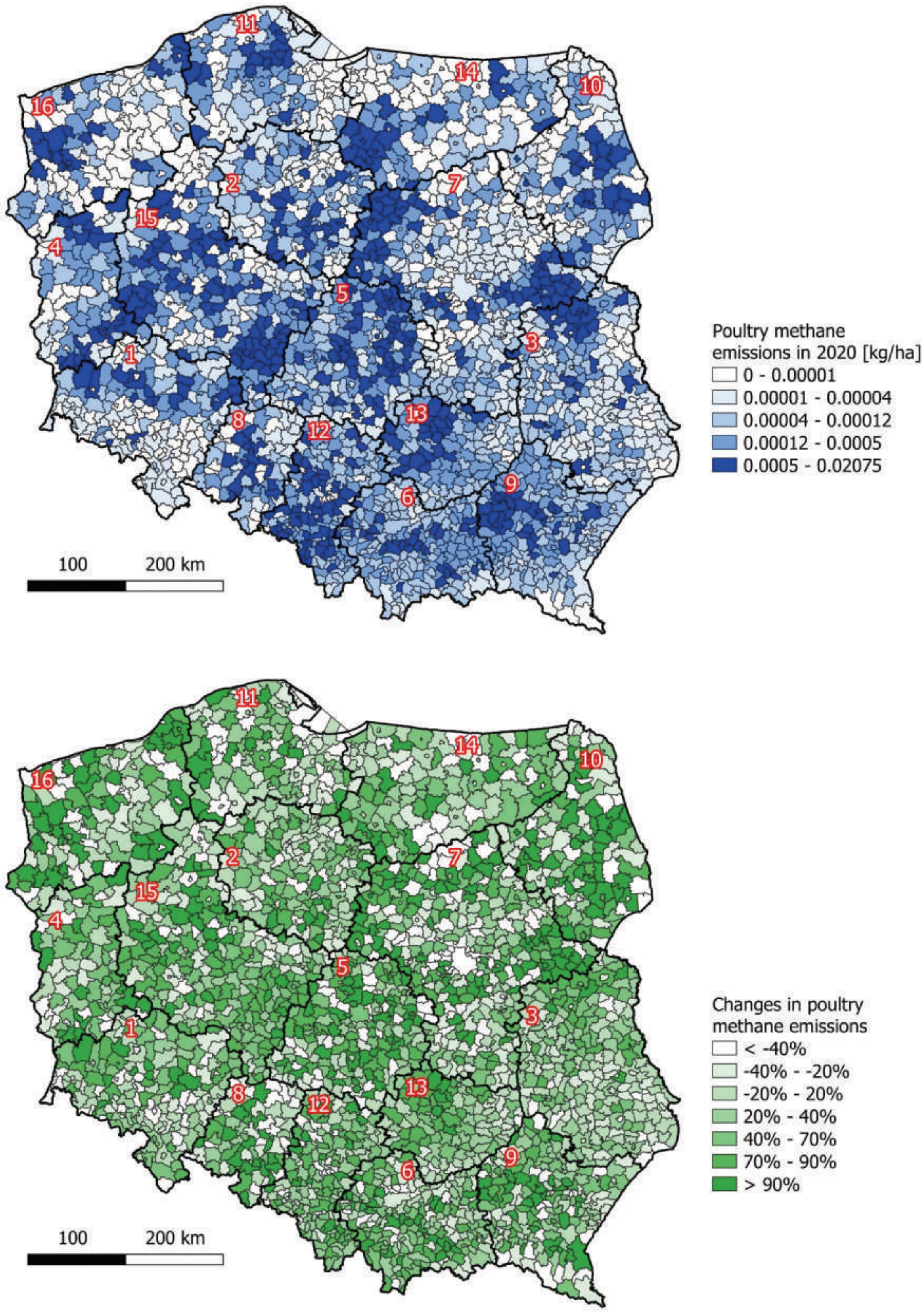

Figure 6. Spatial distribution of poultry CH_4 emission (kg ha^{-1}) in 2020 and its changes between 2010 and 2020 [%]. Voivodship IDs: 1 - Dolnośląskie; 2 - Kujawsko-Pomorskie; 3 - Lubelskie; 4 - Lubuskie; 5 - Łódzkie; 6 - Małopolskie; 7 - Mazowieckie; 8 - Opolskie; 9 - Podkarpackie; 10 - Podlaskie; 11 - Pomorskie; 12 - Śląskie; 13 - Świętokrzyskie; 14 - warmińsko-Mazurskie; 15 - Wielkopolskie; 16 - Zachodniopomorskie.

systems, rather than liquid or pasture systems, are widely used in Poland due to lower investment costs, leading to lower amounts of CH_4 produced in aerobic conditions (Eggleston et al., 2006).

Spatial distribution of total livestock CH_4 emissions

Poland's livestock farming and thus CH_4 emissions are highly regionally differentiated. Our results showed that the emissions between 16 voivodships varied between 8 and 106 Gg. The highest CH_4 emissions from livestock farming were found in northeastern Poland on the border of the Mazowieckie, Podlaskie, and Warmian-Masurian Voivodships (Figure 2). Significant emissions were also recorded in Wielkopolska, where the increase was one of the highest (17.7%). These results are consistent with the increasing total livestock populations in these regions of Poland, particularly in Podlaskie Voivodship. This particular region of Poland has the lowest index of valuation of agricultural acreage (WRPP) (55.0 points) and is characterized by weak agricultural potential due to poor, strongly acidic, and acidic soils, cold climate, and short vegetation period. On the other hand, the yield of meadow hay was above the national average, which was related to the dominant direction of specialization of farms in dairy farming (Madej, 2015). There is a similar regionalization in the Polish literature, highly correlated with the livestock population and its changes over time at the voivodship level. In a study by Mielcarek-Bocheńska & Rzeźnik (2018) in the years 2007–2016, similar regional variations were observed, with the highest emissions in Podlaskie and Wielkopolskie Voivodships. In the remaining provinces, including Mazowieckie, the average CH_4 emissions were lower than 45 Gg. Moreover, the emissions for the period 2007–2016 had increasing trend with the average annual CH_4 emission of 30 ± 23.8 Gg. Our results showed the increasing trend of CH_4 emissions with the average value of 34.8 ± 8 Gg for 16 voivodships in 2020. The declining trend in emissions was observed in the southern regions and along the western border with the highest decrease in Podkarpackie (33.4%), Świętokrzyskie (21.3%), and Małopolskie (20.8%) Voivodships. These regions of Poland, despite their medium condition for agricultural production, are characterized by a high number of small farms (less than 5 hectares) focused on supplying the owners with the sale of surpluses on the local market (Ośrodek Doradztwa Rolniczego, 2020). In addition, a limiting factor is the development of urbanism and the potential employment in bigger cities, as well as the change from agriculture production to tourism in mountainous regions (Bański & Mazur, 2010; Wysocka-Czubaszek, Czubaszek, et al., 2018). The lowest emissions were also observed in Lubuskie Voivodship, both in 2010 and 2020, which is consistent with a study by Charkovska et al. (2019). In the remaining voivodships, CH_4 emissions were at an average level, with no significant increases or decreases, due to the predominance of farms with crop production and a decrease in the number of dairy farms (Poczta & Bartkowiak, 2012). In a study by Wysocka-Czubaszek, Banaszuk, et al. (2018), changes in total CH_4 emissions from agriculture at a regional scale in Poland from 1999 to 2015 were observed at a similar level. Voivodships with significantly highest amounts of CH_4 emissions were Mazowieckie, Wielkopolskie, and Podlaskie, while the lowest emissions were observed in Lubuskie, Podkarpackie, Małopolskie and Świętokrzyskie Voivodships.

Spatial distribution of CH_4 emissions from dairy cattle

A slightly increase in dairy cattle CH_4 emissions from 2010 to 2020 across Poland has been observed, with the average emissions of 19.8 ± 5 Gg. The emissions dominated in northeastern Poland, especially in Podlaskie Voivodship, with an increase of 15.2% in ten years, related to the growing dairy cattle population (Figure 3). Similar results were obtained in a study by Wysocka-Czubaszek, Banaszuk, et al. (2018) where emissions in Podlaskie Voivodship oscillated around 80 Gg till 2015 with an increasing trend, whereas for the whole of Poland, a decreasing trend was observed. The highest emissions were observed in the Mazowieckie Voivodship, both in 2010 and 2020, however, the increase was not significant (5.1%). Despite the low decline in the dairy cattle population, milk production has increased significantly since EU accession, especially in the Mazowieckie, Wielkopolskie, and Warmian-Masurian Voivodeship, where large dairy farms predominate (Pepliński, 2022). Significantly lower values were found in southern Poland, where the highest decline in emissions occurred in Podkarpackie, Świętokrzyskie, Małopolskie and Lubelskie Voivodships (from −36.7% to −21.1%). These results are consistent with the highest decline in the dairy cattle population from −41.9% to −27.6%. In the study by Pepliński (2022), based on the CSO database, the decline in the dairy cattle population in the periods 1990–1994 and 2016–2020 also occurred in the southern part of Poland. Moreover, the highest decrease in milk yield was observed for the same regions. The reason for that is the previously mentioned occurrence of small farms with cattle kept for self-supply and neighbourhood milk sales (Dzun, 2012). Noticeable changes have also occurred in Lubuskie Voivodship, where the increase in CH_4 emissions was the highest among other regions (33.9%), due to a 22.9% increase in the dairy cattle population. However, Lubuskie Voivodship is characterized by the intensification of crop production, in particular the increase in the share of cereals in total agricultural production from 26% in 2004 to 30% in 2014, mainly at the expense of a reduction in livestock production (Mierzejewski & Polcyn, 2014). Hence, the lowest CH_4 emissions from dairy cattle production across Poland were observed in this particular voivodship.

Spatial distribution of CH_4 emissions from non-dairy cattle

For non-dairy cattle, the average emissions increased by 24% and reached 12 ± 3 Gg in 2020. The highest CH_4 emissions from non-dairy cattle were observed in Wielkopolska Voivodship, as well as the highest increase, of 45.9% from 2010 to 2020 (Figure 4). Similar results were obtained in the study by Wysocka-Czubaszek, Banaszuk, et al. (2018) and Charkovska et al. (2019), where non-dairy CH_4 emissions were predominant in Wielkopolska. The most important factor was the increase in non-dairy cattle population by 30% from 2010 to 2020. High emissions were also noticeable for Mazowieckie, Podlaskie, and Kujawsko-Pomorskie Voivodships, where the emissions increased by 25.4%, 32.9%, and 21.4%, respectively. The lowest emissions were found in Podkarpackie, Lubuskie, Dolnośląskie, and Zachodniopomorskie Voivodships. However, in Lubuskie Voivodship, despite the low emission values, one of the highest increases in CH_4 emissions (by 26.6%) has again been observed, consistent with the increasing non-dairy cattle population. Furthermore, the decrease has been observed only for three southern regions – Podkarpackie (−12.2), Świętokrzyskie (−4.5%), and Małopolskie (−1.5%) Voivodships, where the non-dairy cattle population has decreased the most by 2020, by −31.3%, −17.8% and −17.7%, respectively.

Spatial distribution of CH_4 emissions from swine

CH_4 emissions from swine have decreased in all voivodships in Poland due to a significant decline in the swine population. The lowest emissions in 2020 have been observed in western, southern, and eastern regions of Poland, while the highest were in Wielkopolskie, Mazowieckie, Łódzkie and Kujawsko-Pomorskie Voivodships (Figure 5). Swine production in Poland has been declining since 2006, both in the number of sows and the number of slaughtered fatteners. The main reason is the introduction of ASF red zones and the unprofitability of piglets and fattening pig production, a consequence of the Polish breeding herd's low reproductive rate, significant piglet losses, and high feed conversion rates (Dors et al., 2013). Consequently, Poland's swine population decreased, especially in the case of smaller farms (Pepliński, 2023). Hence, most swine production comes from large industrial farms in particular regions of Poland. According to a study by Skorupski (2012), most of the large-scale farms are located in Wielkopolskie, Mazowieckie, Zachodniopomorskie, Kujawsko-Pomorskie and Łódzkie Voivodships, which is consistent with our results. In addition, CH_4 emissions from swine in several municipalities increased between 2010 and 2020, mainly in Przechlewo (Pomorskie), Tuszyn, Grabica, Moszczenica (Łódzkie), Pielgrzymka (Dolnośląskie). These results are consistent with a study by Pepliński (2023), in which the highest changes in swine population from 2010 to 2020 occurred in the above-mentioned regions, especially in Przechlewo and in the three municipalities of Łódzkie Voivodship.

Spatial distribution of CH_4 emissions from poultry

The CH_4 emissions from poultry were calculated only for manure management since there is no emissions factor for enteric fermentation. The emissions were significantly lower than in the rest of the livestock categories, however, with an increasing trend in almost every voivodship – the highest in Mazowieckie, Wielkopolskie, Podlaskie and Zachodniopomorskie Voivodships (Figure 6). Over the years, these voivodships have specialized in poultry production, driven by the European market (Pepliński, 2022). The only exception where a decrease has been observed was Pomorskie Voivodship and in the western and southern Poland – Małopolskie, Śląskie, Podkarpackie, Dolnośląskie and Lubuskie Voivodships. Moreover, in these particular regions, a decline in poultry population from 2010 to 2020 was also observed. The highest point emissions were observed in several municipalities where large poultry farms are located, according to data reported (Skorupski, 2012). These municipalities were located in Wielkopolskie (Rawicz), Śląskie (Lubliniec), Mazowieckie (Bieżuń, Radzanów, Szreńsk, Żuromin), and Zachodniopomorskie (Kobylanka, Krzęcin) Voivodships.

Conclusions

The study aimed to analyse the spatial distribution of CH_4 emissions from livestock farming in Poland at the municipal level (LAU-2) in 2010 and its changes in 2020, based on livestock population data from COS's NAC reports and EFs from UNFCCC NIR 2010 and 2020. The livestock population and EFs in each animal category have changed over the past decade, leading to fluctuations in CH_4 emissions. Total CH_4 emissions from livestock farming in Poland increased slightly over the decade. The highest emissions were observed in voivodships where livestock farming was predominant, namely Mazowieckie, Podlaskie, and Wielkopolskie voivodships. Notably, significant changes in CH_4 emissions occurred in Podlaskie, Lubuskie, and Wielkopolskie Voivodships, where livestock production experienced considerable growth during the same period. Conversely, the lowest emissions were primarily found in southeastern and southwestern Poland, where the decrease in livestock population was most pronounced among all voivodships. The changes in livestock population and EFs in Poland over the past decade have been influenced mainly by EU standards and Common Agricultural Policy, including factors such as milk limits and fluctuations in milk prices, the unprofitability of piglets and fattening swine production, and the outbreak of ASF disease. Therefore, conducting studies on livestock farming and its changes in Poland based on available reports and databases is crucial. Estimating CH_4 emissions at the municipal level (LAU-2) provides a highly detailed spatial picture compared to traditional national or regional assessments. This granularity allows for targeted mitigation efforts in areas with high emissions. Analysing emissions for two points in time (2010 and 2020) allows the study to identify trends and changes in emissions across different regions. This information is crucial for evaluating the effectiveness of existing policies and developing new strategies to address rising emissions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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