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6. Carbon footprint assessment and greenhouse gas emissions (GHGs) from Agricultural Soils

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Introduction

Carbon footprint assessment and greenhouse gas emissions (GHGs) from agricultural soils play a vital role in understanding the contribution of agriculture to global climate change. From ancient times, agriculture has been one of the most crucial components for human beings. With the evolution of human societies, agricultural practices also transformed to meet the growing demands of people. In the modern world of the 21st century, climate change has become one of the major problems of the technologically advanced world, contributing significantly to carbon footprint and greenhouse gas emissions (IPCC, 2023). Agricultural soils act as both sources and sinks of greenhouse gases, emitting carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) through processes such as soil organic matter decomposition, fertilizer application, irrigation, and land-use changes. Among these gases, nitrous oxide is particularly important due to its high global warming potential and long atmospheric lifetime. As per the Global Carbon Budget 2024, published in the journal Earth System Science Data by the Global Carbon Project, global fossil fuel carbon dioxide emissions reached approximately 37.4 gigatonnes in 2024, reflecting a continuous increase in the global carbon footprint (Friedlingstein et al., 2024). Therefore, accurate assessment of GHG emissions from agricultural soils is essential for developing climate-smart agricultural practices, improving soil management, and supporting mitigation strategies aimed at reducing emissions while ensuring food security.

Does Agriculture feed or promote Climate change?

Climatic change has become a serious concern for living beings due to its threatening impacts like global warming,

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droughts, floods, environmental hazards and disaster, economic losses, all of which affects agricultural productivity and food security (IPCC, 2023).

To confront these challenges, agricultural climate smart practices are crucial to reduce greenhouse gas emissions and carbon footprint. But agriculture also plays a dual role in climate change (Smith et al., 2014) which includes:

1) Contributing to climate change:

The most significant gases emitted from agricultural systems are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Tubiello *et al.,* 2022).

Nitrous oxide is mostly emitted from synthetic and organic nitrogen fertilizers by the nitrification and denitrification processes done by soil microbes. (Mosier *et al.,* 2006).

Methane (CH_4) is produced during enteric fermentation in ruminant livestock such as cattle, sheep, and goats.Flooded rice paddies create anaerobic conditions that support methanogenic microbes, resulting in substantial CH_4 emissions. (Gerber et al., 2013; Conrad, 2009).

Additionally stored carbon released from vegetation and soil because of deforestation, mining and conversion of forest lands into agricultural lands.When natural ecosystems such as grasslands are converted to agricultural production, 20–40% of the soil organic carbon (SOC) is lost over time, following cultivation. (Lal, 2004; Smith et al., 2014).

2) Potential mitigator of climate change:

By adopting Climate Smart agricultural practices make agricultural systems effective carbon sinks. Practices like no tillage, cover cropping, reduction in synthetic fertilizers, integrated nutrient management and diverse crop rotations enhance carbon sequestration and significantly reduce nitrous oxide emissions from soil. (Lal, 2015; Hillier *et al.,* 2009).

For effective climate change mitigation through agriculture, the following recommendations were made

(i) There is a need for a systematic redirection of investment, funding, research and policy focus towards sustainable agriculture. (FAO, 2013).

(ii) Agricultural policies that encourage farming by subsidizing safe and sustainable farm inputs should be encouraged.

(iii) Extension services should promote awareness-raising about sustainable agriculture.

(iv) Sustainable agriculture should be integrated into all levels of the education system. (World Bank, 2020).

Carbon footprint assessment In Agriculture:

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Carbon footprint assessment is the process of measuring greenhouse gases produced by various activities like farming, daily life processes and human activities. The concept of carbon foot printing has been in use since several decades but known differently as life cycle impact category indicator global warming potential. Therefore, the present form of carbon footprint may be viewed as a hybrid, deriving its name from "ecological footprint", and conceptually being a global warming potential indicator (ISO 14040; Pandey *et al.,* 2011).

Carbon footprint assessments involve:

1. Life Cycle Assessment (LCA) models calculating GHGs across all farm inputs and outputs. (ISO 14044).
2. Field-based Global Warming Potential (GWP) measurements capturing CO_2, N_2O, and CH_4 emissions. (Smith et al., 2014)
3. Yield-scaled metrics (e.g., kg CO_2-eq per tonne of produce) for cross-system comparisons (Burney et al., 2010).

The methodologies for carbon footprint calculations are still evolving and it is emerging as an important tool for greenhouse gas management.

Need of carbon footprint assessment:

- It helps to identify the main source of GHG-emissions which helps us to understand and focus on real problems.
- Support to find the most sustainable way to confront these problems and prevent resource wastage.
- Promote climate smart practices and decision making based on accurate emission data
- Protects ecosystems by creating awareness and responsibilities among people and organisations.

Carbon footprint assessments are essential because they identify hotspots of emissions, help prioritise mitigation options, and inform policy and market incentives like carbon credits.FAO, 2021). Robust, transparent measurement and reporting systems are emerging as essential components of sustainable agri-value chains.

Greenhouse Gas-emission:

Greenhouse gases trap heat in the earth's atmosphere, maintaining the temperature that suits life as if this effect didn't exist. The average earth's temperature will be -18°C(0°F) instead of current ~15°C (IPCC, 2023). But as we know excess of everything is bad, which is happening with GHGs, causing threatening environmental hazards and degrading natural habitat and adaptation of living beings because of multiple anthropogenic activities.

Source of GHG-emissions:

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- Burning of fossil fuels for meeting the demands of energy for electricity, transport and heating (EPA, 2023).
- Use of excess input application (like fertilizers, insecticides, pesticides) and livestock enteric fermentation in agriculture Tubiello et al., 2022).
- Deforestation, illegal mining, conversion of natural ecosystem for land use change
- Industrial processes such as cement, steel, and chemical production also release significant emissions (EPA, 2023).

Solutions for reducing Carbon footprint and GHG- emissions

1. Conservation Agriculture

Conservation agriculture focuses on minimum soil disturbance, permanent soil cover, and diversified cropping systems. Practices such as no-tillage or reduced tillage significantly lower carbon dioxide (CO_2) emissions by limiting soil oxidation and reducing the breakdown of soil organic matter. When soil is not repeatedly disturbed, organic carbon remains protected within soil aggregates, enhancing long-term carbon sequestration. Improved soil structure under conservation agriculture enhances water infiltration, root development, and microbial activity, which collectively improve soil health and productivity. Studies have shown that minimal tillage systems often exhibit lower yield-scaled carbon footprints compared to conventional plough-based systems, meaning fewer emissions per unit of crop produced. Additionally, reduced fuel consumption from fewer tractor operations directly lowers fossil-fuel-based emissions. Over time, conservation agriculture contributes to climate resilience by improving soil moisture retention and reducing erosion, making it a key strategy for sustainable intensification while mitigating greenhouse gas emissions from agricultural systems.

2. Crop Residue Management

Crop residue management involves retaining crop residues on the soil surface or incorporating them judiciously rather than burning them. Residue retention protects soil from erosion, moderates soil temperature, and enhances soil organic carbon stocks through gradual decomposition. Avoiding residue burning is particularly important, as burning releases large amounts of CO_2, methane (CH_4), and nitrous oxide (N_2O), contributing significantly to air pollution and climate change. Practices such as mulching and cover cropping promote microbial activity that stabilizes carbon in soil while improving nutrient cycling. According to Pretty et al. (2018), residue retention and cover crops not only increase soil carbon sequestration but also reduce methane emissions associated with residue

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burning. Additionally, residues improve soil water-holding capacity, reducing irrigation needs and indirectly lowering energy-related emissions. In the long term, effective residue management enhances soil fertility, supports biodiversity, and contributes to climate-smart agriculture by balancing productivity with reduced greenhouse gas emissions.

3. Optimise Nutrient Management

Optimised nutrient management aims to match nutrient supply with crop demand in terms of rate, timing, source, and placement. Efficient fertilizer use significantly improves nitrogen use efficiency (NUE), thereby reducing nitrous oxide (N_2O) emissions, one of the most potent greenhouse gases from agriculture. Excess or poorly timed nitrogen applications lead to volatilization, leaching, and denitrification, all of which increase emissions and reduce farm profitability. Balanced nutrient management, including the use of soil testing, site-specific nutrient recommendations, and integrated use of organic and inorganic fertilizers, minimizes unnecessary inputs. Mosier et al. (2006) highlighted that improved fertilizer management can substantially cut emissions while maintaining yields. Additionally, reducing excess fertilizer use lowers indirect carbon emissions associated with fertilizer manufacturing, packaging, and transportation, which are energy-intensive processes. Overall, optimized nutrient management contributes to climate mitigation, cost savings for farmers, and improved soil and water quality.

4. Water Management Practices

Water management plays a crucial role in regulating greenhouse gas emissions, particularly methane emissions from flooded rice systems. Practices such as Alternate Wetting and Drying (AWD) reduce the anaerobic conditions responsible for methane production in paddy soils. By allowing the soil to dry periodically, methane emissions can be reduced by up to 30–50% without compromising rice yields. Adjusting irrigation schedules and improving water-use efficiency also lowers energy consumption associated with pumping and distribution, thereby reducing carbon emissions. Sander et al. (2017) emphasized that improved irrigation management can significantly mitigate greenhouse gas emissions while conserving scarce water resources. Efficient water use also minimizes nutrient losses and enhances root growth, contributing to better crop performance. In a climate-change context, water-smart practices increase resilience to droughts and erratic rainfall while ensuring sustainable productivity and reduced environmental impact.

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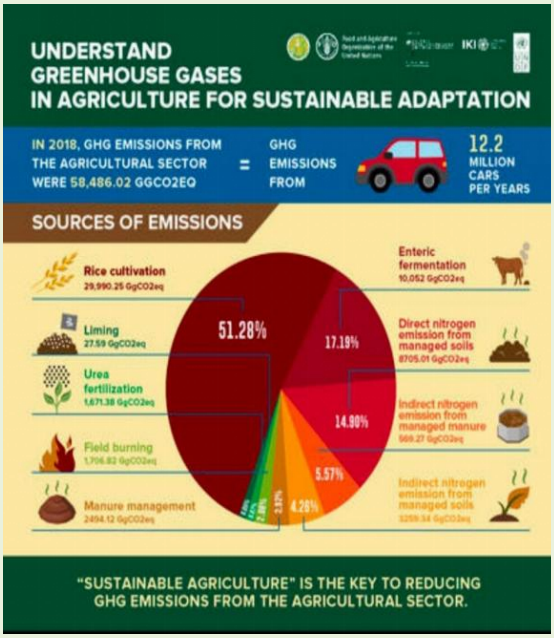
5. Integrated Crop–Livestock Systems & Agroforestry

Integrated crop–livestock systems and agroforestry enhance system diversity and resource efficiency, leading to lower overall carbon footprints. Incorporating trees, shrubs, or legumes into farming systems increases carbon sequestration in biomass and soils while improving nutrient cycling. Livestock integration allows crop residues to be recycled as feed, reducing waste and enhancing farm efficiency. Trees in agroforestry systems act as long-term carbon sinks, storing significant amounts of carbon above and below ground. Leguminous components fix atmospheric nitrogen, reducing the need for synthetic fertilizers and associated emissions. These diversified systems also improve soil structure, water retention, and biodiversity, making farms more resilient to climate stress. By distributing production risks and reducing dependence on external inputs, integrated systems lower emissions per unit of output while enhancing livelihoods. Thus, crop–livestock integration and agroforestry are effective nature-based solutions for climate-smart agriculture.

6. Regenerative and Smart Farming Technologies



Regenerative agriculture and smart farming technologies focus on restoring ecosystem functions while improving efficiency through innovation. Precision agriculture tools such as GPS-guided machinery, soil sensors, drones, and decision-support systems enable precise input application, reducing overuse of fertilizers, water, and pesticides. This targeted approach lowers greenhouse gas emissions and improves resource-use efficiency. Regenerative practices—such as diversified crop rotations, cover cropping, and organic amendments—enhance soil organic carbon and biological activity, contributing to long-term carbon sequestration. According to FAO (2021), digital and smart technologies play a critical role in reducing agriculture's environmental footprint while sustaining productivity. Automation and real-time monitoring also reduce fuel use and labor

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inefficiencies. By combining ecological principles with advanced technology, regenerative and smart farming systems promote sustainable intensification, climate mitigation, and resilience, making them essential tools for future low-carbon agricultural development.

Understand greenhouse gases emission in agriculture (source: Thailand's Fourth National communication {2022)

Climate Smart agricultural (CSA) practices:

Climate-smart agriculture (CSA) is an approach that helps guide actions to transform agri-food systems towards green and climate resilient practices. It has become a real time frame for scientists, governments and farmers to combat the challenges of the modern world. As in the research held in climate smart villages across Ghana used greenhouse flux measurements from rice, legumes and other crops to know change after adopting the Climate Smart Agricultural practices and it was observed that there is significant reduction in the emission of greenhouse gases like in rice it was 298 kg CO_2-eq/ha reduction per crop cycle. (Aggarwal et al., 2018).

Key sectors of Climate-Smart Agriculture

Importance

Agricultural sectors must become climate-smart to successfully tackle current food security and climate change challenges. Agriculture, including forestry and fisheries, is crucial for food security and rural incomes as well as other essential products, such as energy, fiber, feed and a range of ecosystem services.

Climate-smart agriculture is a pathway towards development and food security built on three pillars:

- Increasing productivity and incomes
- Enhancing resilience of livelihoods and ecosystems and
- Reducing and removing greenhouse gas emission from the atmosphere (FAO, 2013).

Challenges

Climate Smart agricultural practices involve the use of information and communication technology for efficient farm management that prioritizes productivity, profitability, and the

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conservation of natural resources. But there are many real ground challenges, facing in its full implementation which are:

- High initial investment is required for setting up and use of new technologies. .e.g. Drip irrigation system which reduces water wastage 40-50% compared to traditional way of irrigation system but their high cost demotivates the farmers to use it
- Awareness among farmers about CSA practices is very low, if farmers know about it they don't have proper understanding of it. In India, less than 30% of smallholder farmers have knowledge about it, due to which maximum farmers prefer to use traditional ways.
- Real time data of climate and weather is crucial for CSA practices but many rural areas lack it, making sowing, input application difficult.
- Poor policy and infrastructure create a huge challenge for it. As policies are made, their on-ground actions are highly inefficient, making its importance and presence poor among people. (Singh et al., 2021; World Bank, 2020).

Conclusion

Climate-smart agricultural practices provide a harmonious, long-lasting means of handling these two issues. This is achieved by combining methods that assess carbon footprints. These practices ensure that large emitting sectors within agriculture are identified, thus helping agriculture transition from an emitter of greenhouse gases to becoming an agent that contributes to solving the problem of climate change. It is important that these practices receive greater emphasis in terms of awareness, technology, and policies that promote higher levels of agricultural resilience.

References

Aggarwal, P.K., Jarvis, A., Campbell, B.M., Zougmoré, R.B., Khatri-Chhetri, A., Vermeulen, S.J. and Loboguerrero, A.M. (2018) 'The climate-smart village approach: Framework for scaling up adaptation options in agriculture', Ecology and Society, 23(1), p.14.

Burney, J.A., Davis, S.J. and Lobell, D.B. (2010) 'Greenhouse gas mitigation by agricultural intensification', Proceedings of the National Academy of Sciences of the United States of America, 107(26), pp.12052–12057.

Conrad, R. (2009) 'The global methane cycle: Recent advances in understanding the microbial processes involved', Environmental Microbiology Reports, 1(5), pp.285–292.

ISSN: 3107-3638 (Online)

FAO (2013) Climate-smart agriculture sourcebook. Rome: Food and Agriculture Organization of the United Nations.

FAO (2021) Greenhouse gas emissions from agri-food systems: Global, regional and country trends. Rome: Food and Agriculture Organization of the United Nations.

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Peters, G.P., Peters, W., Pongratz, J., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B. and Zaehle, S. (2024) 'Global carbon budget 2024', Earth System Science Data, 16, pp.1–170.

Hillier, J., Hawes, C., Squire, G., Hilton, A. and Smith, P. (2009) 'The carbon footprints of food crop production', International Journal of Agricultural Sustainability, 7(2), pp.107–118.

IPCC (2023) Climate Change 2023: Synthesis Report. Geneva: Intergovernmental Panel on Climate Change.

ISO (2006a) ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Geneva: International Organization for Standardization.

ISO (2006b) ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: International Organization for Standardization.

Lal, R. (2015) 'Sequestering carbon and increasing productivity by conservation agriculture', Journal of Soil and Water Conservation, 70(3), pp.55A–62A.

Mosier, A.R., Syers, J.K. and Freney, J.R. (2006) Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment. Washington, DC: Island Press.

Sander, B.O., Wassmann, R., Siopongco, J.D.L.C. and Nguyen, V.H. (2017) 'Alternate wetting and drying in rice production: A practical mitigation option for methane emissions', Field Crops Research, 203, pp.1–13.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo-Abad, C., Romanovskaya, A., Sperling, F. and Tubiello, F. (2014) 'Agriculture, forestry and other land use (AFOLU)', in Climate Change 2014: Mitigation of Climate Change. Cambridge: Cambridge University Press.

Tubiello, F.N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S., Halldórudóttir Heiðarsdóttir, H., Wanner, N., Smith, P. and Federici, S.

ISSN: 3107-3638 (Online)

(2022) 'Pre- and post-production processes dominate greenhouse gas emissions from agri-food systems', Earth System Science Data, 14, pp.1795–1809.

World Bank (2020) Climate-smart agriculture: Policies, practices and financing. Washington, DC: World Bank.

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