Maintaining agricultural sustainability through carbon footprint management

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Global awareness of climate change issues, particularly changes in air temperature, has increased dramatically over the last half a century. Concerns regarding ecosystem sustainability and human existence on Earth arise due to population expansion, rising surface temperatures and increased greenhouse gas (GHG) emissions. Agriculture accounts for approximately 18% of the total GHG emissions, largely in the form of carbon dioxide, methane and nitrous oxide. As a result, limiting GHG emissions is critical to alleviating the consequences of climate change, which is attainable if the concept of carbon footprint is understood. Cereal production produces more GHG emissions than other farming methods, including vegetables and fruits. 'Carbon footprint' is a popular term in agriculture and environmental research due to its involvement in environmental impact assessments and global climate change. GHG emissions are influenced by changes in land use, soil type and agricultural management approaches. Therefore, it is important to consider how agricultural management practices, particularly those involving the soil and related systems, affect the relationships between photosynthesis and GHG emissions. This study deals with the concept of carbon footprint in agriculture and various mitigation measures for its management.

Keywords: Agricultural management, carbon footprint, climate change, greenhouse gas emissions, soil health.

GLOBAL discussions regarding the anthropogenic influence of climate change are taking place for the last 50 years, as the harmful impact of rising temperatures is now widely acknowledged by the scientific and non-scientific populations. By the end of this century, the Earth's surface temperature is projected to increase by 1.6°C to 5.8°C due to rapid population growth and greenhouse gas (GHG) emissions[1]. Therefore, lowering GHG emissions in the atmosphere is a crucial task that can be accomplished by understanding the carbon footprint. A strategy to quantify the overall GHG impacts and understand the carbon footprint can help distinguish expected emissions from their main sources. Hence, using carbon footprint calculations to guide emission reductions and understanding the risk of global warming is useful[2].

According to Gao *et al.*[3], the term 'carbon footprint' is 'a measurement of the total GHG emissions caused directly or indirectly through an organisation, an individual, or a product, and is expressed in terms of carbon dioxide equivalent (CO_2e)'. Therefore, carbon footprint of a person or an activity is measured in weights of kilogram or mg of carbon. There are many ways to estimate carbon footprint, from straightforward online tools to sophisticated models, life-cycle analyses and input–output-based techniques and tools. The agricultural sector faces a number of problems, the most important of which is the need to produce high-quality and enough food to feed the world[4]. Rice is responsible for a significant amount of methane (CH_4) emissions, particularly in India and China, but livestock is the main source of emissions in Australia, generating around 62.8 MMT CO_2, accounting for roughly 70% of the total agricultural GHG emissions[5]. The use of chemicals, electricity and fossil fuels in agriculture is the main cause of emissions due to the increasing population. The rate of soil carbon sequestration input is much lower than the rate of natural resource exploitation in terms of fossil fuels, minerals and carbon utilization from the soil[6].

Therefore, agricultural practices need to be reviewed, and environment-friendly strategies should be adopted. This study aims to improve our understanding of the contribution as well as management of carbon footprints by agricultural practices.

Carbon footprint

The concept of carbon footprint is derived from that of ecological footprint[7]. The volume of biologically productive

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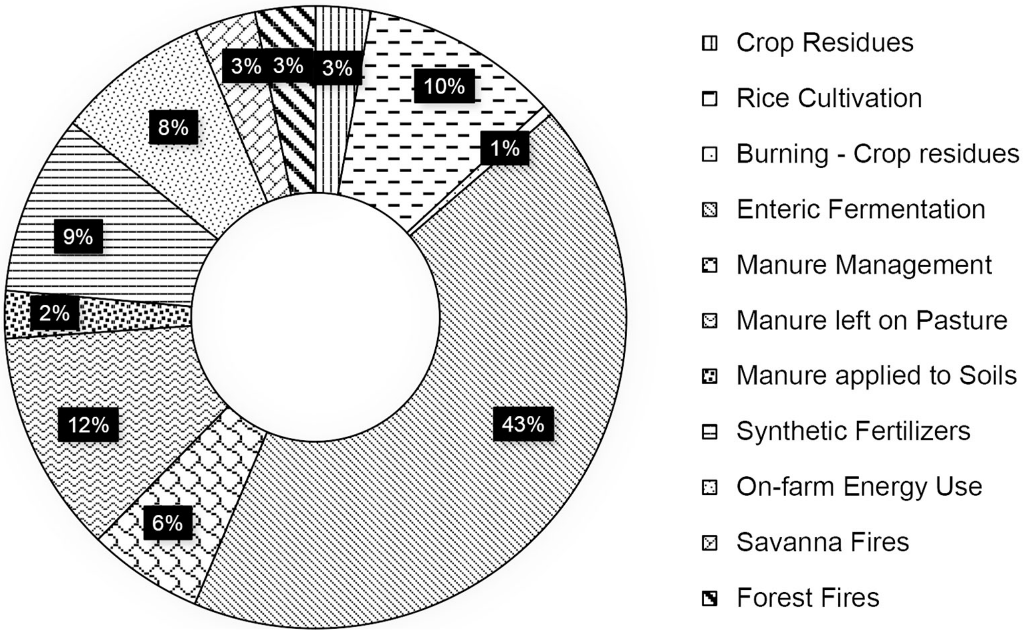

Figure 1. Contribution of various agricultural subsectors contributing to total carbon footprint. (Adopted from FAOSTAT[13].)

land and water necessary to support a certain human population is referred to as the ecological footprint. It is expressed in global hectares. Wiedmann and Minx[8] defined carbon footprint as a specific quantity of gaseous emissions associated with climate change, human production or consumption activity.

Previously, only carbon dioxide (CO_2) was included when calculating the carbon footprint, but today, all important GHG emissions, including CO_2, CH_4 and nitrous oxide (N_2O), are calculated in terms of CO_2e. CO_2 gas contains one unit of CO_2e, whereas CH_4 and N_2O contain 23 and 298 units of CO_2e respectively. For all gases, the global warming potential is generally defined as a carbon footprint per unit area, i.e. kg CO_2e/ha. The following formula is used to determine agricultural carbon footprint[9]

$$\text{Carbon footprint} = \frac{\sum(\text{Agricultural input} \times \text{GHG emission coefficients})}{\text{Grain yield}}.$$

The International Organization for Standardization (ISO) 14001 accreditation is a starting point for possible environmental health obligations. Factors such as the carbon footprint have generated interest in international standards recognition. The application of current technologies and adherence to international standards necessitates a balance of economic and environmental factors[10]. As a result, there has been a surge in interest in tracking carbon loss through GHG emissions, and carbon sequestration from agricultural and non-agricultural regions. Higher soil temperatures result in greater CH_4 and N_2O emissions[11]. Increased microbial activity is associated with greater soil respiration rates, which are inversely related to soil oxygen content[11]. Despite the fact that interactions between moisture and temperature impacts occur continuously in the field, GHG emissions generally increase from winter to summer and reduce from summer to winter due to changes in temperature and soil moisture content[12]. The soil GHG emissions are significantly influenced by agricultural practices. GHG emissions are found to increase significantly due to a number of agricultural practices and activities, such as livestock rearing, soil ploughing, tillage, fertilizer application, irrigation, crops and associated machineries[13]. The use of fossil fuels by machinery for power generation and livestock husbandry are the two largest contributors to GHG emissions (Figure 1). The carbon impact of agriculture can be divided into three categories. Tier 1 includes all direct GHG emissions from the soil and farm machineries. Tier 2 includes indirect emissions from power generation, while tier 3 includes indirect emissions from manufacturing and transporting agricultural fertilizers and pesticides[14].

Models to estimate carbon footprint

Various models have been developed to minimize agricultural emissions in the future. Since agriculture has significant carbon footprint, the developed models aid in estimating the consequences and possible mitigation solutions for the agricultural system. The carbon footprint of various crops, such as wheat, canola, maize and sunflower, is estimated using emission factor approaches. Some models are simple, focusing just on biomass, yield, soil carbon, other soil qualities, manure input and so on, while others are sophisticatedly incorporating dynamic crop–climate–soil models.

Table 1. Models for the assessment of soil carbon dynamics influencing carbon footprint

Model	Inputs
Roth C	Soil temperature, soil water and clay content
C-TOOL	Mean monthly air temperature, clay content, C/N ratio and carbon in organic inputs
ICBM	Crop type, soil temperature, rainfall, soil characteristic and tillage frequency
Day Cent	Daily minimum/maximum temperature and precipitation, soil texture, vegetation type and amount and timing of nutrient amendment
DNDC	Site and climate, crop, tillage, fertilizer and manure amendment, plastic film use, flooding, irrigation, grazing and cutting
CERES-EGC	Weather, soil properties, crop management and soil organic matter
Info-RCT	Precipitation, manure/residue application, SOC, human labour, animal labour, machine and seeds
Roth C	Soil temperature, soil water and clay content

Table 2. Carbon footprint of some crops

Crops	Carbon footprint ($kg\ CO_2e/kg$)	Country	Reference
Rice	1.60	China	26
Wheat	0.75		
Maize	0.48		
Maize	0.21–0.24	India	27
Sunflower	0.875	Iran	21
Cotton	1.60	Australia	28
Soybean	0.186	Brazil	29
Rice	0.53	Thailand	30
Rapeseed	0.768	Italy	31
Sunflower	0.889		

C-TOOL[15], Introductory Carbon Balanced Model (ICBM)[16] and Rothamsted Carbon (Roth C)[17] are a few examples of simple carbon models. Soil characteristics like water content, crop type, soil temperature and clay content are considered in these models (Table 1).

Carbon footprint in the agricultural sector

Agriculture, forestry and other land use account for 24% of total world GHG emissions[18]. Management practices such as tillage, inorganic fertilization, pesticides, manuring, harvesting, waste management and composting contribute to carbon footprint[19]. As a result, research on sustainable agricultural practices is necessary to address these problems. The largest source of fossil fuel-derived energy used in agriculture leads to GHG emissions[20]. The use of electricity in agriculture contributes a major portion towards carbon footprint (78.7%)[21].

Rainfed agriculture has a lower carbon footprint than irrigated agriculture because irrigation-related emissions are lower, and the areas are smaller, necessitating manual labour[22]. Diesel is used to transport seeds, herbicides, fertilizers and other farm equipment, and the tillage process contributes to majority of the emissions. Diesel contributes 19% and 6% of the overall carbon footprint in the rice–mustard cropping system employing conventional tillage and no-tillage techniques respectively[23]. However, using fertilizers, transportation, and manufacturing considerably increase GHG emissions. Between 2000 and 2010, nitrogenous fertilizers resulted in 89% of the carbon footprint in India, whereas phosphorus (4%) and potassium (2%) had minimal influence. Pesticides also contributed 2% of the overall carbon footprint over the same period[24].

Methane emissions from paddy soils, which are influenced by applying nitrogenous fertilizers, constitute a major portion of the total GHG emissions. The methane emissions account for approximately 49.5% of the overall carbon footprint associated with rice cultivation. Initially, at lower nitrogen fertilizer rates, the carbon sequestration rate is positive. Specifically, nitrogen fertilizer rates between 0 and 300 kg N/ha have been observed to facilitate this transition, with paddy fields functioning as carbon sinks during this range of nitrogen fertilizer application rates[25]. Table 2 gives the carbon footprint of different crops[26–31].

According to Gerber *et al.*[32], enteric fermentation from ruminants accounts for approximately 40% of anthropogenic methane emissions. This reveals the substantial contribution of farm animals to carbon footprint. Methane emissions ranging from 120 to 250 g were recorded per day per cow, depending on diet and management practices[33]. Dietary interventions, such as the use of feed additives like methane inhibitors or adjustments in feed composition, have shown potential to reduce methane emissions. Additionally, improved animal management practices and manure management techniques can contribute to methane mitigation[34].

Carbon footprint management

Crop diversification and summer fallow

The carbon footprint of agricultural products varies depending on the species and cultivation methods. The diversion of some rice fields to other less water-demanding crops increases irrigation efficiency, fertilizer use efficiency and water productivity, reducing carbon footprint (Figure 2). Cultivation of wheat after leguminous crops leads to 20% lower GHG emissions compared to cultivation after cereals[35]. The factors that determined carbon footprint included crop biomass and nitrogen content[36]. Summer fallowing improves productivity and nitrogen availability[35]. The decrease in the frequency of summer fallowing may be an effective strategy to reduce carbon footprint. Legume cropping significantly reduced carbon footprint compared to summer fallowing.

Rice cultivation

Yao *et al.*[37] recommended cultivating rice using a ground cover system, which covers the crop with a thin plastic sheet to maintain moisture levels and reduce carbon footprint and direct emissions from flooding. This process increases rice yield while lowering overall carbon emissions.

System of rice intensification (SRI) can be a potential substitute for wetland paddy cultivation as a practice for carbon footprint management. Wassmann *et al.*[38] examined the carbon footprint of SRI in the Philippines. They found that SRI, with its reduced water requirement and intermittent flooding, resulted in lower methane emissions compared to conventional flooded paddy fields.

Neue *et al.*[39] evaluated the carbon footprint of SRI systems compared to conventional rice cultivation in China. The study demonstrated that the SRI approach, which promotes alternate wetting and drying (AWD) irrigation practices, substantially reduced methane emissions, thereby positively impacting the carbon footprint of rice cultivation.

Residue retention

Keeping crop residues in no-tillage systems helps prevent soil organic carbon (SOC) loss. Nitrogenous fertilizers generate 36–52% of total emissions, and higher nitrogen fertilizer efficiency might reduce the carbon footprint of field crops. Similarly, enhanced soil carbon sequestration reduces the carbon footprint because atmospheric (CO_2) input carbon is transformed into plant biomass and eventually returned to the soil[35]. Plastic-film mulching and biodegradable-film mulching, on the other hand, dramatically enhanced the net potential for global warming and carbon footprint compared to no-mulching[40].

Crop residue mulching and no-tillage significantly improve the organic carbon content of the soil and help stabilize soil aggregates. Reduced tillage increased the total and recalcitrant carbon pools in a rice–wheat cropping system[41].

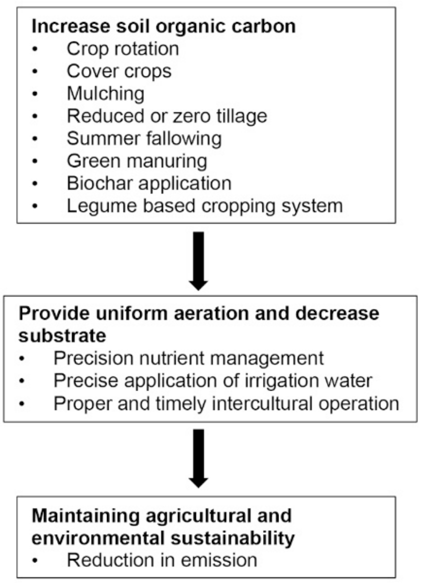

Figure 2. Carbon footprint management through agricultural practices.

Organic agriculture and soil organic carbon

Organic farming has been found effective in sequestering carbon. Organic farming contributes towards reducing the carbon footprint of agriculture[42]. The crude protein form of nitrogen present in animal feed causes GHG emissions. Dietary concentrations results in increased CH_4 emissions since they increase the amount of undigested material in manure, and when that material degrades, it releases CH_4 (ref. 43). Composting manure in organic farming can cut N_2O emissions and CH_4 emissions in half. Burning fossil fuels and straw are practices that directly release terrestrial carbon into the atmosphere. Practices for increasing SOC include conservation tillage, integrated nutrient management, mulching, cover crops and a variety of cropping systems. SOC plays an important role in quantifying carbon footprint.

Adopting no-tillage methods with natural mulch to reduce soil evaporation losses and using irrigation techniques like drip irrigation should be considered good practices towards sustainable agriculture. Conservation agriculture, according to a meta-analysis, improved SOC in the Indo-Gangetic plains and sub-Saharan Africa through decreased tillage, crop residue assimilation and crop diversification[44].

Application of nitrogen fertilizers

The introduction of legumes in crop rotation is a key strategy to decrease the direct N_2O emissions from the soil, as legumes require less nitrogen fertilizers. Proper application of nitrogen fertilizers can help in the mitigation of emissions. Several techniques, such as Green Seeker and leaf colour chart (LCC)-based urea application, have been developed to apply only the required amount of fertilizers. According to Bhatia *et al.*[45], the LCC-based urea application resulted in a 10.5% reduction in the global warming potential (GWP) of the rice–wheat system. Although carbon footprint was reported lowest when no nitrogen fertilizer was used, significant yield loss occurred.

Conclusion

Agriculture is a major contributor to climate change due to its high carbon footprint. Field emissions are primarily influenced by crop type, water and fertilizer needs. Due to irrigation requirements and CH_4 emissions, rice has the highest carbon footprint. Some recommended solutions for reducing emissions include appropriate fertilizer usage, irrigation management, reduced tillage frequency, organic farming, crop rotation, etc. As nitrogen fertilizer has the maximum carbon footprint among fertilizers, using different approaches and tools such as Green Seeker, LCC-based urea application, sulphur-coated urea, neem cake, etc. may help lower the carbon footprint.

To develop an ecological farming approach and preserve the environment, the present study will help farmers and other stakeholders take environment-friendly agricultural decisions.

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