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Impact of climate change on agriculture and farming tactics to reduce the carbon footprint of crop cultivation in sub-tropical ecosystem: A review

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Abstract

The human population on the planet is estimated to reach 9 billion by 2050; this requires significant increase of food production to meet the demands. Climate change and agriculture are interrelated processes, both of which take place on a global scale. Climate change affects agriculture in a number of ways, including through changes in average temperature, rainfall, and climate extremes. Climate change associated with rise in concentration of green house gases (CH_4, N_2O, CO_2 and CFC) is likely to affect crop production. Major impact of warmer temperatures was during the reproductive stage of development and in all cases grain yield in maize was significantly reduced by as much as 80-90% from a normal temperature regime. The combined (CO_2 and temperature) effects of climate change; it appears that pigeon pea incurring an 8% reduction in potential grain yield, also groundnut can be expected to incurring a 30% reduction compared to current potential, sorghum a 22% reduction and maize a 25% reduction. Farming systems have been identified as a viable means to increase grain production. However, farming intensification requires more inputs such as fertilizers, pesticides,

And fuels; all these emit greenhouse gases and have environmental consequences. we present key farming tactics that are proven to be effective in increasing grain production while lowering carbon footprint using diversified cropping systems can reduce the system's carbon footprint by 32 to 315 % compared with conventional monoculture systems; improving N fertilizer use efficiency can lower the carbon footprints of field crops as N fertilizer applied to these crops contributed 36 to 52 % of the total emissions; adopting intensified rotation with reduced summer fallow can lower the carbon footprint by as much as 150 %, compared with a system that has high frequency of summer fallow; enhancing soil carbon sequestration can reduce carbon footprint, as the emissions from crop inputs can be partly offset by carbon conversion from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil; using reduced tillage in combination with crop residue retention can increase soil organic carbon and reduce carbon footprints; integrating key cropping practices can increase crop yield by 15 to 59 %, reduce emissions by 25 to 50 %, and lower the carbon footprint of cereal crops by 25 to 34 %; and including N2-fixing pulses in rotations can reduce the use of inorganic fertilizer, and lower carbon footprints. With the adoption of these improved farming tactics, one can optimize the system performance while reducing the carbon footprint of crop cultivation.

Keywords: Agriculture and farming, carbon footprint, ecosystem, warming temperatures

Introduction

The impacts of climate change include warming temperatures, changes in precipitation, and increases in the frequency or intensity of some extreme weather events, and rising sea levels. These impacts threaten our health by affecting the food we eat, the water we drink, the air we breathe, and the weather we experience. Agriculture releases to the atmosphere significant amounts of CO_2, CH4, and N_2O (Cole *et al.*, 1997; IPCC, 2001; Paustian *et al.*, 2004) [1, 3]. CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (Smith, 2004; Janzen, 2004) [4-5, 6]. CH4 is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (Mosier *et al.* 1998) [7]. N_2O is generated by the microbial transformation of nitrogen in soils and manures, and is often enhanced where available nitrogen (N) exceeds plant requirements, especially under wet conditions (Oenema *et al.*, 2005; Smith and Conen, 2004) [8, 4-5]. Agricultural greenhouse gas (GHG) fluxes are complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation. Many of these mitigation opportunities use current technologies and can be implemented immediately. Agricultural N_2O emissions are projected to increase by 35-60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003) [2].

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Similarly, Mosier and Kroeze (2000) estimated that N_2O emissions will increase by about 50% by 2020 (relative to 1990). If demands for food increase, and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced, and perhaps also a reduction in emissions per capita food consumption. If CH4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60% up to 2030 (FAO, 2003) [2]. However, changes in feeding practices and manure management could ameliorate this increase.

The term “Carbon Footprint” (CF) is spreading rapidly in the media throughout the world because the issues tied to climate change have taken on major relevance in international political debate. Human population on the earth is continuously growing and thus the global demand for food, feed, fiber, and fuel will increase continuously for at least another 40 years (God fray *et al*. 2010). So the practices to expanding cropping areas by clearing more uncultivated lands to increase grain production is possible, but this approach often comes at the expense of reducing carbon stocks in natural vegetation and soils (Whitfield 2006). Converting carbon-rich forests or grasslands to croplands for grain production causes the rapid loss of carbon reserves on the planet (Lal 2004; Pan 2011) [3]. There is a huge gap between the present level of crop yields and yield potential, and this yield gap could be narrowed or even closed, at least on those underperforming farmlands. Success of achieving this goal depends on the use of improved agronomical practices, the enhancement of resource use efficiencies, and the adoption of new farming approaches. However, farming has significant environmental consequences. In particular, increased use of inorganic fertilizers and pesticides in high-yielding farming systems, increases carbon emissions, as most crop production inputs serve as the major sources of greenhouse gas emissions. Also, application rates of inorganic fertilizers and pesticides may accelerate the degradation of farmland, making farming unsustainable for the long term (Fumagalli *et al.* 2011). More importantly, the general public is becoming more aware and concerned about the effect of farming on environmental sustainability and society health as a whole (West *et al*. 2013).

The Greenhouse Effect

The term "greenhouse effect" continues to see use in scientific circles and the media despite being a slight misnomer, as an atmosphere reduces radioactive heat loss while a greenhouse blocks convective heat loss. The result, however, is an increase in temperature in both cases. Greenhouse effect, a warming of earth surface and troposphere caused by the presence of water vapors, carbon dioxide, methane, and certain other gases in the air. While the sun’s heat enters into atmosphere, the heat has trouble leaving back out our atmosphere. Greenhouse gases are Methane, Carbon dioxide, Nitrous oxide etc. The idealized greenhouse model is a simplification. In reality the atmosphere near the Earth's surface is largely opaque to thermal radiation and most heat loss from the surface is by convection. However radioactive energy losses become increasingly important higher in the atmosphere, largely because of the decreasing concentration of water vapor, an important greenhouse gas. Rather than the surface itself, it is more realistic to think of the greenhouse effect as applying to a layer in the mid-troposphere, which is effectively coupled to the surface by a lapse rate. A simple picture also assumes a steady state, but in the real world, the diurnal cycle as well as the seasonal cycle and weather disturbances complicate matters. Solar heating applies only during daytime. During the night, the atmosphere cools somewhat, but not greatly, because its emissivity is low. Diurnal temperature changes decrease with height in the atmosphere. CO_2 is produced by fossil fuel burning and other activities such as cement production and tropical deforestation. Measurements of CO_2 from the Mauna Loa observatory show that concentrations have increased from about 313 parts per million (ppm) in 1960, passing the 400 ppm milestone on May 9, 2013. The current observed amount of CO_2 exceeds the geological record maxima (~300 ppm) from ice core data.

Table 1: Greenhouse gas emission from Indian agriculture

Source	CH_4 (MT)	N_2O (MT)	CO_2 (MT)
Rice cultivation	3.37	-	84.24
Agricultural soil	-	0.22	64.70
Crop residue burning	0.25	0.01	8.21
Total	3.62	0.23	157.15

Sources of increase in atmospheric concentration of gases

Emissions of CO_2 by fossil fuel combustion have increased drastically during the 20th century. The global C budget for the last two decades of the 20th century, lists known sources and sinks, and identifies the magnitude of the so-called missing or fugitive C (Prentice, 2001) [56]. The global C budget for the decade of 1980s included 5.4 F 0.3 Pg C emission by fossil fuel combustion and cement production, and 1.7 F 0.8 Pg C emission by land use change. The latter consists of deforestation and biomass burning, and conversion of natural to agricultural ecosystems. The annual increase in atmospheric concentration of CO_2 during the 1980s was 3.3 F 0.2 Pg C/year, absorption by the ocean was 2.0 F 0.8 Pg C/year, and the unknown residual terrestrial sink was 1.9 F 1.3 Pg C/year. For the decade of the 1990s, emission by fossil fuel combustion and cement production were 6.3 F 0.4 Pg C/year, and the emission by land use change was 1.6 F 0.8 Pg C/year. The increase in atmospheric concentration, however, occurred at the rate of 3.2 F 0.1 Pg C/year, the ab sorption by the ocean was 2.3 F 0.8 Pg C/year and the uptake by an unknown terrestrial sink was 2.3 F 1.3 Pg C/year (Prentice, 2001; Schimel *et al*., 2001) [56, 58]. These global C budgets are tentative at best, because possible emissions of C by soil erosional and other degradative processes are not accounted for. Nonetheless, the data indicate an important role that land use; soil management and terrestrial ecosystems play in the global C budget. Thus, a complete understanding of the components (pools and fluxes) of the global C budget is required to identify sources and sinks of C and develop strategies for mitigating the risks of climate change. There are five principal global C pools. The oceanic pool is the largest, followed by the geologic, pedologic (soil), biotic and the atmospheric pool. All these pools are inter-connected and C circulates among them. The pedologic or soil C pool comprises two components: SOC and the soil inorganic carbon (SIC) pool. The SIC pool is especially important in soils of the dry regions. The SOC concentration ranges from a low in soils of the arid regions to high in soils of the temperate regions, and extremely high in organic or peat soils. The SOC pool also varies widely among ecoregions, being higher in cool and moist than warm and dry regions. Therefore, the total soil C pool is four times the biotic (trees, etc.) pool and about three times the atmospheric pool. There are some estimates of the historic loss of C from geologic and terrestrial pools and transfer to the atmospheric pool. From 1850 to 1998, 270 F 30 Pg of C were emitted from fossil fuel burning and cement production (Marland *et al*., 1999) [56]. Of this, 176 F 10 Pg C were absorbed by the atmosphere (Etheridge *et al*., 1996; Keeling and Whorf, 1999) [49, 53], and the remainder by the ocean and the terrestrial sinks. During the same period, emissions from land use change are estimated at 136 F 55 Pg C (Houghton, 1995, 1999) [50, 51]. There are two components of estimated emissions of 136 F 55 Pg C from land use change: decomposition of vegetation and mineralization/oxidation of humus or SOC. There are no systematic estimates of the historic loss of SOC upon conversion from natural to managed ecosystems. Jenny (1980) [52] observed that ‘‘among the causes held responsible for CO2 enrichment, highest ranks are accorded to the continuing burning of fossil fuels and the cutting of forests. The contributions of soil organic matter appear underestimated.’’

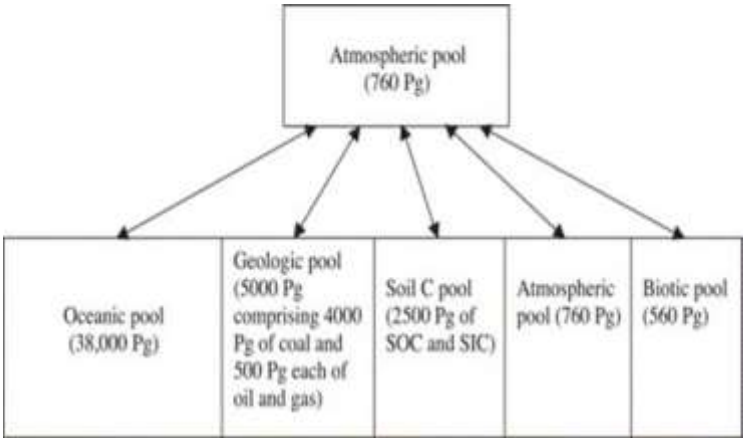


Fig 1: Atmospheric concentration of gases

The historic SOC loss has been estimated at 40 Pg by Houghton (1999) [51], 55 Pg by IPCC (1996) and Schimel (1995) [57], 500 Pg by Wallace (1994) [59], 537 Pg by Buringh (1984) [60] and 60 – 90 Pg by Lal (1999) [54]. Until the 1950s, more C was emitted into the atmosphere from the land use change and soil cultivation than from fossil fuel combustion. Whereas the exact magnitude of the historic loss of SOC may be debatable, it is important to realize that the process of SOC depletion can be reversed. Further, improvements in quality and quantity of the SOC pool can increase biomass/agronomic production, enhance water quality, reduce sedimentation of reservoirs and waterways, and mitigate risks of global warming.

Fig 1: Impacts of Climate Change on Agriculture

Climate change has significant implications for our health. Rising temperatures will likely lead to increased air pollution, a longer and more intense allergy season, the spread of insect-borne diseases, more frequent and dangerous heat waves, and heavier rainstorms and flooding. At the same time, extreme temperatures, a decrease in water availability and changes to soil conditions will actually make it more difficult for plants to thrive. Overall, climate change is expected to stunt plant growth. Changes in temperature, atmospheric carbon dioxide (CO2), and the frequency and intensity of extreme weather could have significant impacts on crop yields.Recent studies done at the Indian Agricultural Research Institute indicate the possibility of loss of 4 – 5 million tons in wheat production in future with every rise of 1oC temperature throughout the growing period. Rice production is slated to decrease by almost a tone/hectare if the temperature goes up by 2 o C. In Rajasthan, a 2oC rise in temperature was estimated to reduce production of Pearl Millet by 10-15%. If maximum and minimum temperature rises by 3oC and 3.5 °C respectively, then Soybean yields in M.P will decline by 5% compared to 1998. Agriculture will be worst affected in the coastal regions of Gujarat and Maharashtra, as fertile areas are vulnerable to inundation and Stalinization. Standard agronomical practices were followed to prepare field inside FACE and tunnels. Seeds of respective variety were sown in treatment facilities and the plants were administered with recommended dose of fertilizers. Rice plants were raised normally and transplanted to cement pots for exposure. The plants kept under water and nutrient non-limiting conditions were subjected to enriched levels of CO2at 550 ppm and warmer temperature regimes maximum up to~4°C above ambient throughout crop growth season. *(PDF)* Yield response of important field crops to elevated air temperature and CO_2level. Economic yield of these crops were calculated. The temperature increase in tunnels however, was not linear butin fractions like ~1.5, 2.8, 3.2°C etc. To have uniform responses, change in yield per degree temperature increase (thermal effect per degree increase of temperature) was calculated and represented for 1, 2, 3 and 4°C increase (PDF) Yield response of important field crops to elevated air temperature and CO_2 level.

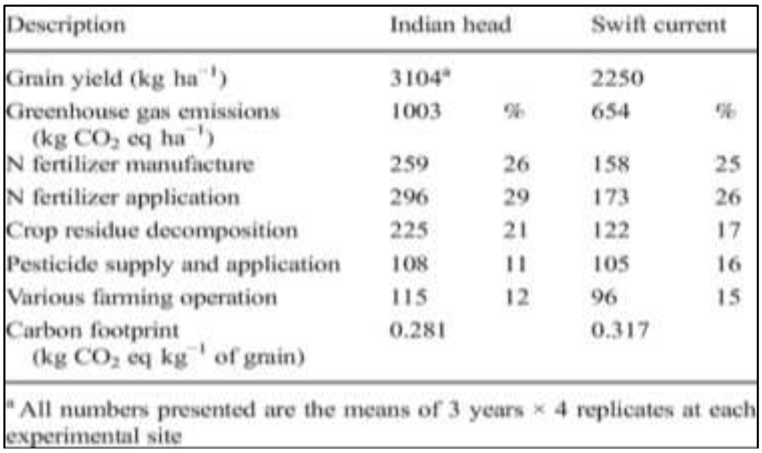
Carbon footprint

Greenhouse gas emissions are one of the key indicators in assessing the environmental sustainability of farming. To quantify the impacts, we define and use the term carbon footprint using the two metrics throughout the article: (A) the total amount of greenhouse gas emissions per unit of farmland—quantifying the total amount of emissions in crop production that focuses more on environmental health and (B) the quantity of greenhouse gas emissions associated with per kilogram of grain produced- emphasizing both emissions during the production of a crop as well as the products (i.e., grain yield) associated with per unit of emission. The latter focuses on increasing crop yield while reducing the greenhouse gas emissions. Recently, both the European Union and the Carbon Trust have attempted to define the concept of Carbon Footprint in a tangible and comprehensive manner on the basis of scientific studies carried out in recent years. According to European Union (2007), Carbon footprint is the overall amount of carbon dioxide and other Greenhouse gas emission (CH_4, N_2O, CFC etc.) associated with a product (goods and services) along its life cycle. Carbon Trust (2008) have also given the another definition, Carbon footprint is the total set of Greenhouse gas emission caused by an individual or organization, event or product.

Environmental conditions and carbon footprint

Climatic conditions have a large impact on the adaptation of crop species (Cutforth *et al.* 2007) [61] and their footprints (Yang *et al*. 2014) [25], and the intensity of the effect depends on various factors. An obvious phenomenon is the quantity of precipitation during a crop growing season that can affect N_2O emission intensity. For example, in the southern region of Saskatchewan, Canada, the long-term (1971–2010) average growing season (1 May–31 Oct) precipitation was 264 mm and the potential evaporation was 635 mm at the drier Swift Current site, and values were 317 and 605 mm, respectively, at the wetter Indian Head site. The water deficit was greater at Swift Current (371 mm) than at Indian Head (288 mm). In response to the water deficit, the average direct emission factors for soil N_2O emission from synthetic N application and crop residue decomposition were found to be at 0.0044 kg N_2O–N kg^{-1} N at Swift Current, 34 % lower than that at Indian Head.

Table 2: Environmental conditions and carbon footprint



Description	Indian head		Swift current	
Grain yield (kg ha^{-1})	3104[a]		2250	
Greenhouse gas emissions (kg CO_2 eq ha^{-1})	1003	%	654	%
N fertilizer manufacture	259	26	158	25
N fertilizer application	296	29	173	26
Crop residue decomposition	225	21	122	17
Pesticide supply and application	108	11	105	16
Various farming operation	115	12	96	15
Carbon footprint (kg CO_2 eq kg^{-1} of grain)	0.281		0.317	

[a] All numbers presented are the means of 3 years × 4 replicates at each experimental site

Nitrogen, phosphorous, and pesticides are the main inputs in the production of barley crops. Weather conditions affect the direct and indirect emissions of the crop inputs. In a barley study, the emission due to the use of N fertilizer (manufacture, transportation and application) was 331 kg CO_2 eq ha^{-1} at Swift Current and 555 kg CO_2 eq ha^{-1} at Indian Head. Consequently, the barley grown at the drier Swift Current location had about an 11 % greater carbon footprint than barley grown at Indian Head (0.317 vs. 0.281 kg CO_2 eq kg^{-1} of grain, respectively). Although total emissions at Indian Head were generally greater than those at Swift Current, barley yields were greater at Indian Head. We defined that the carbon footprint of a field crop as a function of grain yield and total greenhouse gas emissions. Thus, to lower the carbon footprint of field crops, one could employ various means to (I) increase grain yield without increasing greenhouse gas emissions, (ii) decrease greenhouse gas emission without decreasing grain yield, and (iii) more ideally, increase crop yield while at the same time decreasing greenhouse gas emissions.

Contributing to the climate change and carbon footprint by Agriculture

There are various factors that contribute to the greenhouse gas emissions associated with the production of a field crops. Emissions from Agriculture production are mostly derived from various factors.

1. Decomposition of crop residue
2. Inorganic fertilizers application
3. Soil carbon gains or losses from various cropping systems
4. Tillage operations, spraying pesticides, planting and harvesting the crop
5. Manufacture of Inorganic fertilizers.
6. Crop rotations to reduce carbon footprint

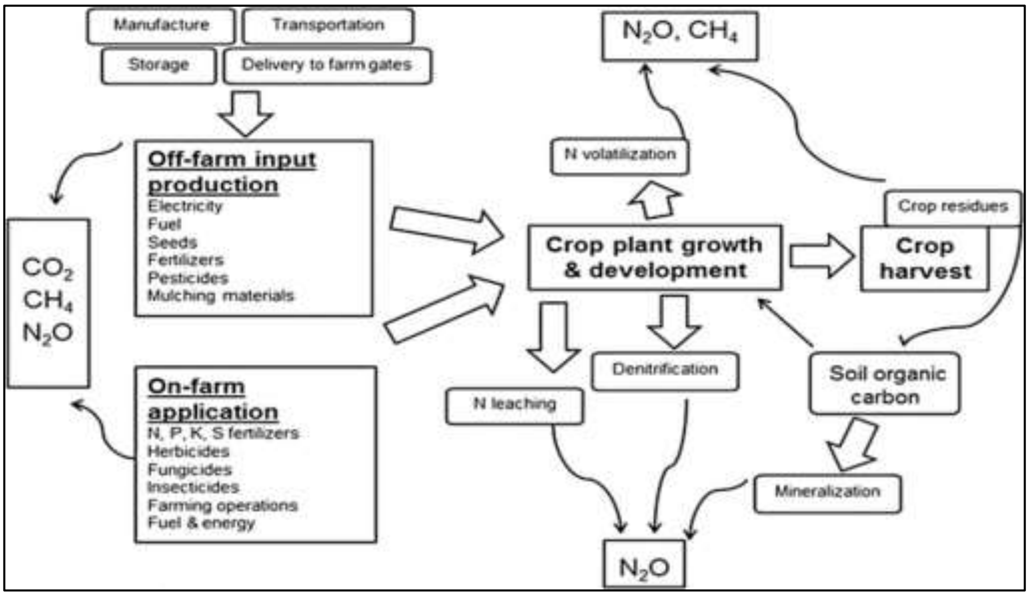


Fig 1: Climate change and carbon footprint by Agriculture

The major contributors to greenhouse gas emissions in crop production include the emissions associated with off-farm manufacture, transportation, and delivery of input products to the farm gate and the emissions during the crop growth period and after harvest. In the calculation, the boundaries are set for a full "Life-Cycle-Assessment" analysis.

Decomposition of crop residue

An abundance of C and other nutrients are returned to the soil through decomposition of crop residues and biological nutrient cycling. Since organic matter (OM) is known to maintain soil aggregate stability, the addition of crop residues often improves soil structure and aggregation. Decomposition also affects soil cover by crop residues and accumulation of soil organic matter, i.e., crop residue management relies on decomposition of the residues to return organic carbon to the soil (Bailey and Lazarovits 2003). The crop residue serves as an important N source in the soil for nitrification and denitrification, contributing directly and indirectly to N2O emissions (Forster *et al.* 2007) [11]. The amount of emissions from the decomposition of the straw and roots depends on the net productivity of the crop, N concentrations of the plant matter, environmental conditions such as soil moisture and temperature, and the duration from spring thaw to fall freeze up (Rochette *et al.* 2008) [14]. Studies in southern Saskatchewan, Canada, show that a large portion (25 %) of the total emissions is attributed to the decomposition of straw and roots for a cereal crop, such as durum wheat (*Triticum durum* L.) produced on the semiarid northern Great Plains (Gan *et al*. 2011) [13]. In the production of grain crops, the carbon footprint can be reduced by effective management of straw and roots, by adopting, for example, the improved production practices such as no-till cropping.

Inorganic fertilizers application

During an experiment found the emission of various gases like CO_2, N_2O and CH_4. De Urzedo *et al.* (2013) [10] the application of organic wastes to soils significantly increased the emissions of carbon dioxide and nitrous oxide. The composition and organic content of labile carbon present in the materials studied had a significant influence on N_2O emissions. However, the use of organic wastes produced very small losses of carbon as CO_2 and did not overcome a loss of 1% relative to the amount of carbon added to the soil. The total emission included direct and indirect emissions through volatilization of NH_3 and N_2O, leaching of nitrate from the application of N fertilizers on farm fields (27 % of the total emissions), and emissions associated with the production, transportation, storage, and delivery of N fertilizers to the farm gate (38 %). The intensity of the emissions associated with N fertilization depends on the ratio of precipitation to potential evapo-transpiration during the period when the N fertilizer is applied (Gregorich *et al*. 2005) [14]. In western Canada, for example, the carbon footprint of spring wheat is estimated at 0.383 kg CO_2 eq kg^{-1} of grain produced in the semiarid brown soil zone, which was 32 % lower than the carbon footprint (0.533 kg CO_2 eq kg^{-1} of grain) of the same wheat crop produced in the more humid black soil zone (Gan *et al*. 2011) [13]. The main contributor to the large difference in the spring wheat carbon footprint between the two soil zones was precipitation and the amount of fertilizer applied to the crop.

Soil carbon gains or losses from various cropping systems

Legume-based cropping systems have reduced carbon losses. Reducing fertilizer use and including N_2-fixing pulses to reduce carbon footprint. Nitrogen fertilizer is the main crop input in the production of non-pulse crops, such as canola, mustard, durum wheat, and barley (*Hordeum vulgare* L.). In oilseed production on the Canadian prairie, for example, increasing rates of N fertilizer has been shown to increase greenhouse gas emissions and the carbon footprint. The emissions and the carbon footprint both are a linear function of the rate of N fertilizer applied to the oilseed crops, although the slope of the linear regression varied with crop species. Similarly, N fertilizer is the main contributor to greenhouse gas emissions in cereal production. In durum wheat production, the greenhouse gas emission from the N fertilizer application averaged 223 kg CO_2 eq ha^{-1}, which was more than 16 times the emissions associated with the various farming operations. Furthermore, the emissions and carbon footprint of cereal crops were significantly influenced by the rate of N fertilizer applied to the previous crops in the rotation. Greater greenhouse gas emissions from the barley crop occurred as more N fertilizer was applied to the oilseed crops grown the previous year. In other words, the total emission in the production of the barley crop was a function of the rate of fertilizer N applied to the previous oilseeds. The amount of residual mineral N measured prior to seeding barley increased as the amount of N applied to the previous oilseeds was increased above 90 kg N ha−1. The trend of the effect was similar between two contrasting environments comparing the wetter Indian Head with the drier Swift Current) or among oilseed species. A meta-analysis from 14 different field sites in European shows that the risk of high yield-scaled N_2O emissions in oilseed increases after a critical N surplus (Walter *et al*. 2015). The N_2O emissions can be especially higher in oilseed (as compared with cereals) after harvest due to the higher N contents in oilseed plant residues.

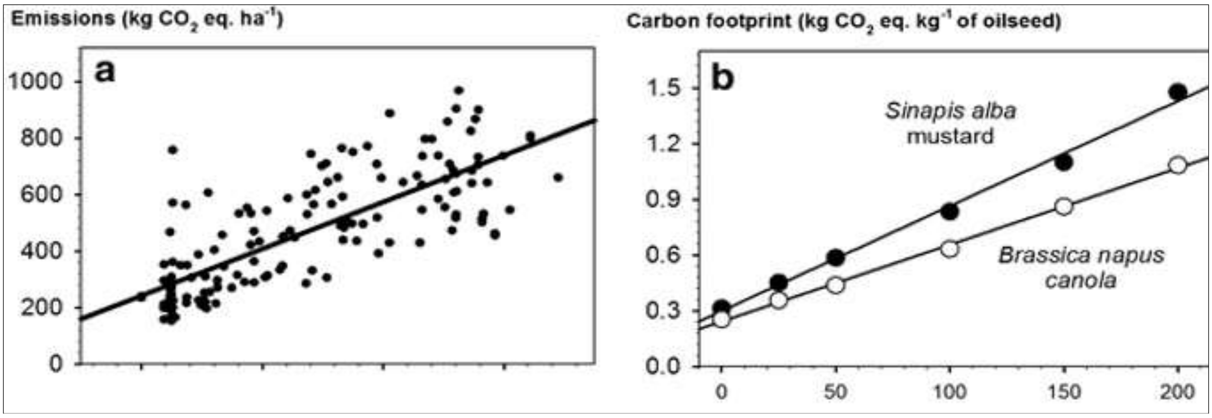


Fig 3: Fertilizer N applied (Kg N ha^{-1})

Increasing the rate of inorganic N fertilizer application to the crops increased (a) the CO2 emissions from crop production resulting in a linear increase of the carbon footprint of the oilseed regardless of the crop species (b).

Including N_2-fixing pulse crops in a crop rotation can significantly decrease greenhouse gas emissions and the carbon footprint of the crop grown the following year. The emissions from the application of N fertilizer averaged 251 kg CO_2 eq ha^{-1} for durum wheat produced in cereal-durum, or oilseed-durum, whereas the durum wheat produced in the pulse-durum system emitted 162 CO_2 eq ha^{-1} or 37 % lower than the durum wheat produced in the cereal- or oilseed-durum system (Gan *et al*. 2011) [13]. As a result, the carbon footprint of durum wheat produced in the cereal-durum crop rotation had an average carbon footprint of 0.42 kg CO_2 eq kg^{-1} of grain. The carbon footprint of durum wheat preceded by a pulse crop, such as chickpea (Cicer arietinum L.), lentil (Lens culinaris Medikus), or dry pea (Pisum sativum L.) the previous year, was lowered to 0.30 kg CO_2 eq kg^{-1} of grain or 28 % lower than when durum wheat was preceded by a cereal crop. Furthermore, crops grown in the previous 2 years had a significant influence on the carbon footprint of durum wheat. An oilseed and a pulse crop alternately grown the previous 2 years (pulse-oilseed-durum, oilseed-pulse-durum, or oilseed-oilseed-durum systems) lowered the carbon footprint of durum wheat by 25 % compared with durum wheat grown in cereal-cereal-durum system. Durum wheat produced in a pulse-pulse-durum system had the lowest carbon footprint, at 0.27 kg CO2 eq kg−1 of grain, or 34 % lower than when the durum wheat was preceded by cereal crops the previous 2 years.

These studies clearly demonstrate that the emissions and the carbon footprint of cereals and oilseed crops is a function of N fertilizer applied to the crops. The decreased use of N fertilization lowers the carbon footprint accordingly. Also, increased N fertilizer application to the crops grown the previous years will increase the total emission of the subsequent crops as a greater amount of soil residue N causes more greenhouse gas emissions. However, the emission intensity can be substantially reduced by including N2-fixing pulse crops in a crop rotation. The inclusion of pulses in the rotation allows the system to rely on the symbiotic N2 fixation from the atmosphere, which significantly decreases the use of synthetic N fertilizer, thus lowering the carbon footprint.

Tillage operations, spraying pesticides, planting and harvesting the crop

A number of studies have investigated how tillage practices may affect the carbon footprint and the published results are inconsistent, varying with climatic conditions, soil type, and cropping systems. In the tropical soils of Zimbabwe, a 9-year study found tillage and residue management significantly impacted soil organic carbon with conventional tillage having the least amount of organic carbon conserved in a Chromic Luvisol red clay soil (Chivenge *et al*. 2007) [27]. Tillage disturbance is the dominant factor reducing soil carbon stabilization within microaggregates in the clayey soil, whereas conservation practices increase soil organic carbon contents. In some cases, reduced tillage in combination with additional carbon input from cover crops significantly improved the soil organic carbon content (Garcia-Franco *et al*. 2015; Pinheiro *et al*. 2015) [31, 35]. Plant residue inputs from green manure and the incorporation into the soil by reduced tillage promoted the formation of new aggregates and activated the subsequent physical-chemical protection of organic carbon. In northwest China, wheat-maize intercropping under reduced tillage with stubble retention increased crop yield by 8 % and reduced greenhouse gas emissions by 7 % compared with conventional tillage (Hu *et al*. 2015). However, soil organic carbon can be gained or lost depending on soil type and land use practices. Soil disturbance affects the quantity and quality of plant residues entering the soil, their seasonal and spatial distribution, and the ratio between above- and belowground inputs (Pinheiro *et al*. 2015; Sainju *et al*. 2010) [35, 22]. Data from India show a linear relationship between carbon input and CO2 output; an increase of 1 Tg CO2 eq $year^{-1}$ of carbon input resulted in a corresponding increase in carbon output of 21 Tg CO_2 eq $year^{-1}$ (Maheswarappa *et al*. 2011) [32]. However, there is uncertainty about how tillage may affect soil organic carbon in some other areas. In a study conducted at eastern Montana, tillage did not influence crop biomass and CO_2 flux nor on total soil carbon content (Sainju *et al.* 2010) [22]. A study in southern Saskatchewan compared soil organic carbon amounts from 1995 to 2005 (Shrestha *et al.* 2013) [36]. After 11 years, soil organic carbon in the 0–15-cm depth was 0.2 Mg C ha^{-1} higher under continuous cereal cropping compared with fallow-cereal systems. There were no significant differences in soil organic carbon content between minimal tillage and no-till practices. The study shows that soil organic carbon differences between tillage systems may require several decades to become distinguishable in this semiarid climate. Tillage may influence mineralizable carbon and microbial biomass (Campbell *et al.* 2005) [29], but these effects do not necessarily increase soil available nutrients or crop yields (Campbell *et al.* 2011) [28].

Herbicides remain the most commonly used weed management practice in the production of field crops in most agricultural regions on the planet (Beckie 2007) [26]. In many cases, fungicides and insecticides are also used in the production of field crops. Each pesticide may have different emission intensity; however, at the present time, emissions for each individual pesticide used in crop production are not readily available. Researchers often assume that the emission factors are similar among products within a similar category, but there is a large difference between crop types in the amount of pesticide used during a given growing season. For example, the contribution to the carbon footprint by the use of pesticides in durum production on the Canadian prairie is often less than those reported in the production of Brassica napus canola or annual pulse crops (Gan *et al.* 2011) [13]. More pesticides are usually required in the production of oilseeds and pulses because severe disease pressure occurs more often in these broadleaf crops than in cereal crops.

Crop rotations to reduce carbon footprint

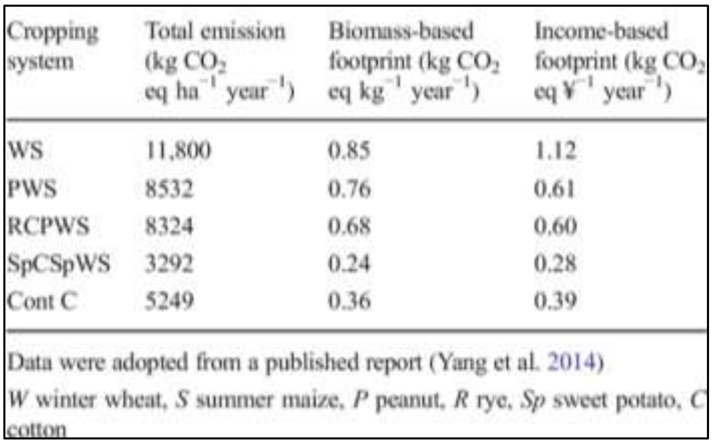
Diversifying

Crop diversification has become increasingly important in many parts of the world (Fig. 5) as a means to control problem weeds (Harker *et al.* 2009; Menalled *et al.* 2001) [44, 46], suppress plant diseases (Kutcher *et al.* 2013) [43], increase production sustainability (Mhango *et al.* 2013) [33], and enhance economics (Zentner *et al.* 2002) [48]. Also, crop diversification has been considered a key cropping practice for improving agroecosystem productivity (Gan *et al.* 2015) [18] and lowering the carbon footprint (Yang *et al.* 2014; Minx *et al.* 2009) [25]. We use a case study to describe the environmental benefits of using diversified systems in the production of field crops.

Lowered carbon footprint

A well-managed field experiment was conducted at the Agroecosystem Station of the Chinese Academy of Science (37° 50′ N, 114°40′ E), in Luancheng, Hebei Province, China. The experimental site was on the northern China Plains (Yang *et al.* 2014) [25]. The experiment, run from 2003 to 2010, included five cropping systems (Table 1): (1) winter wheat/summer maize (Zea mays L.) (2-year cycle), (2) peanut (Arachis hypogaea L.)/winter wheat/summer maize (3-year cycle), (3) rye (Secale cereal L.)/cotton (Gossypium hirsutum L.)/peanut/winter wheat/summer maize (5-year cycle), (4) sweet potato (Ipomoea batatas L.)/cotton/sweet potato/winter wheat/summer maize (5-year cycle), and (5) continuous cotton cropping. Each rotation was cycled on its assigned plots 30 × 7.5 m. Researchers found that the total emissions per unit of land varied significantly among the five cropping systems. Because of the different crops with different types of crop yield, the authors used biomass as the functional unit in the calculation of the carbon footprint of the various rotations. Based on biomass, the diversified 5-year rotation which included sweet potato—sweet potato/cotton/sweet potato/winter wheat/summer maize had the lowest carbon footprint at 0.24 kg CO_2 eq kg^{-1} $year^{-1}$ whereas the least diversified rotation—the 2-year rotation of winter wheat with summer maize had the largest footprint at 0.85 kg CO_2 eq kg^{-1} $year^{-1}$. When the footprint was calculated by using economic values as the functional units, Yang *et al.* 2014 [25] found that the 5-year rotation including sweet potato had the lowest economic footprint, 0.28 kg CO_2 eq $year^{-1}$, while the 2-year rotation of winter wheat with summer maize had the highest economic footprint, 1.12 kg CO_2 eq $year^{-1.}$ A major benefit in lowering the biomass-based footprint for the 5-year diversified rotation was the lack of N fertilizer and a preference for K fertilizer in sweet potato that decreased total carbon emissions. Also, the crop residue from potato, winter wheat and summer maize, and the fallen leaves of cotton, were beneficial in maintaining the soil organic carbon in the top 20-cm soil layer. Increased soil organic carbon offset the input-induced greenhouse gas emissions. Furthermore, the large biomass of sweet potato reduced the biomass-based footprint whereas the higher price of cotton and sweet potato relative to wheat and maize lowered the income-based footprints. In this case study, multiple metrics (biomass and income-based) were used to calculate the footprint of the different cropping systems when analyzing for environmental impacts.

This and other studies clearly demonstrate that diversifying cropping systems in the production of field crops can be effective in increasing total grain production at the system level with reduced carbon footprints. In designing a diverse cropping system targeted at lowering the footprint of the system, one must examine the overall greenhouse gas emissions and the footprint of individual crop species. Crops requiring low production inputs and those with a high yield of straw and roots for incorporation into the soil as carbon are keys to reducing the overall footprint of the system. However, the implementing diversified cropping systems to decrease greenhouse gas emissions in crop production must consider other factors. In the water-scarce Southeast Asian rice (Oryza sativa L.) production areas, changing the traditional double-rice cropping system to a more diversified system that included upland crops reduced irrigation water use in the dry season by about 70 % and decreased CH_4 emissions by 97 % without causing economic penalty (Weller *et al.* 2016). However, this system change resulted in a continuing loss of soil organic carbon and decreasing soil fertility (Weller *et al.* 2015). In Australian sugarcane (Saccharum officinarum L.) production, researchers found significant interactions among soil, climate, and cropping practices that affect the magnitude of N_2O emissions (Thorburn *et al.* 2010). A study across the 30 provinces of China shows that the CO_2 emissions in agriculture was affected by changes in economic development, region-specific industrial structure, and investment and adaptation of new technologies far more than was affected by population density, energy structure, and resource availability (Tian *et al.* 2011).



Cropping system	Total emission (kg CO_2 eq ha^{-1} $year^{-1}$)	Biomass-based footprint (kg CO_2 eq kg^{-1} $year^{-1}$)	Income-based footprint (kg CO_2 eq ¥$^{-1}$ $year^{-1}$)
WS	11,800	0.85	1.12
PWS	8532	0.76	0.61
RCPWS	8324	0.68	0.60
SpCSpWS	3292	0.24	0.28
Cont C	5249	0.36	0.39

Data were adopted from a published report (Yang et al. 2014)

W winter wheat, *S* summer maize, *P* peanut, *R* rye, *Sp* sweet potato, *C* cotton

Intensifying crop rotations with less summer fallowing to reduce carbon footprint

In arid and semiarid regions of the world, the productivity of agroecosystems is often constrained by a low availability of water and nutrients (Rasouli *et al.* 2014) [41]. One of the approaches employed to tackle these challenges is using summer fallow where the land is left unplanted for one growing season. For example, in the mid-1970s, approximately 11 million hectares of farmland were in summer fallow on the Canadian prairies, accounting for approximately 40 % of the total annual crop land of the region. The area of summer fallow has declined substantially in recent years, but still a large portion of the farmland is in summer fallow (FAOSTAT 2014) [17]. During summer fallow, a proportion of the rainfall is conserved in the soil profile (Tanaka and Aase 1987; Tanwar *et al.* 2014) [23, 24], which is then available for crops grown the following year (Sun *et al.* 2013) [42]. Additionally, summer fallowing encourages the release of N via the N mineralization of soil organic matter (Campbell *et al*. 2008) [15], thus increasing soil N availability and helping to reduce the amount of inorganic N fertilizer used in cropping (Koutika *et al.* 2004) [45]. However, a number of studies have shown that the frequency of summer fallow in a cropping rotation has a significant impact on the carbon footprint of the rotation (Gan *et al.* 2012a; O’Dea *et al*. 2013; Schillinger and Young 2014) [19, 21, 48]. Crop intensification with reduced frequency of summer fallow in a rotation can increase crop production while reducing the carbon footprint. Below is a case study conducted in southwest Saskatchewan from 1985 to 2009 (Gan *et al*. 2012a) [19], showing the environmental benefits of reducing the frequency of summer fallowing.

A field experiment was initiated in 1966 at the Agriculture and Agri-Food Canada Research Centre at Swift Current (50° 17′ N, 107° 48′ W). Detailed data on soil carbon were collected for the following four contrasting rotation systems in 25 years (1985–2009): (1) summer fallow-wheat, (2) fallow-wheat-wheat, (3) fallow-wheat-wheat-wheat-wheat-wheat, and (4) continuous wheat. The summer fallow frequency of these systems was taken as 50, 33, 17, and 0 %, respectively. All phases of each system were present every year, and each rotation was cycled on its assigned plots. Each plot is 10.5 by 40 m. Overall, annualized wheat yields across the 25 study years were linearly proportional to growing season (1 May–31 Aug) precipitation; each milli meter of precipitation increasing grain yield by an average 5.26 kg ha−1. Summer fallow frequency interacted with water availability in affecting grain yield. In the dry years, wheat in the fallow-wheat system had lowest annualized grain yield whereas wheat in the three other systems did not differ in yield, averaging 962 kg ha−1. In normal to wetter years, annualized wheat yield differed significantly among the four rotation systems; with the continuous wheat system producing 9, 29, and 56 % more than wheat grain produced by the system that included 17, 33, and 50 % of the summer fallow phase in the rotation, respectively. The grain yield of wheat grown on summer fallow was greater than the yield of wheat grown on stubble; this was largely due to more soil water conserved in the fallow fields under the semiarid environment (O’Dea *et al.* 2013) [21]. However, a higher frequency of summer fallow decreased the annualized yield of the system. The increased grain yield of the wheat crop grown after summer fallow, compared with wheat after wheat, did not overcome the lost opportunistic yield in the summer fallow phase (De Jong *et al*. 2008; Campbell *et al*. 2008) [15]. As a result, wheat in the continuous wheat system produced the highest grain yield and gained highest soil organic carbon over the years, leading to the smallest footprint value at −0.441 kg CO_2b eq kg^{-1} of grain, significantly lower than the footprint for the other three systems which ranged between −0.102 to −0.116 kg CO_2 eq kg^{-1} of grain (Fig. 6). The magnitude of the effects was influenced by water availability. In dry years, the carbon footprint averaged −0.357 kg CO_2b eq kg^{-1} of grain compared with −0.140 kg CO_2 eq kg^{-1} of grain in normal years and −0.093 kg CO_2 eq kg^{-1} of grain in wet years. The highest negative carbon footprint in dry years is attributable to the lowest emissions from least N fertilization and least crop residue decomposition which more than offset the low grain yields. However, when soil carbon gains over the years were excluded, the carbon footprint differed little between the four systems. This case study shows that more intensified wheat cropping practices significantly increases soil carbon gains, increases annualized grain production, and thus lowers the carbon footprint. A study of ten growing seasons in north-eastern Syria showed that the inclusion of pulses either as grain crops or hay in the rotation boosted profits considerably (Christiansen *et al*., 2015). Replacing summer fallow with common vetch (*Vicia sativa* L.) for hay production increased the average gross margin by US$126 ha^{-1} $year^{-1}$, and growing vetch for hay in rotation with wheat produced greater profit than continuous wheat, by $254 ha^{-1} $year^{-1}$. The wheat-vetch-for-grain and wheat-lentil rotations were twice as profitable as wheat fallow or continuous wheat. The benefits of replacing summer fallow with green manures in a rotation system may vary with climatic conditions and local farming practices. In a 2-year study at north-central Montana, replacing summer fallow with legume green manures in a rotation increased the average use efficiency of available N by 24 % during the wheat year and increased total residue carbon and N returned to soils by 260 and 26 kg ha^{-1}, respectively (O'Dea *et al.* 2013) [21]. However, overall wheat yield and protein content were reduced with the replacement of summer fallow with green manures. Previous manure crops may deplete soil water, causing yield reduction for the crops grown in the following years. These studies clearly show that more intensified systems with reduced frequency of summer fallow in the rotation can reduce the system carbon footprint by as much as 250 %. In the Mediterranean-type climate, replacement of summer fallow with a forage or grain legume can more than double farming profits compared with the system with a high frequency of summer fallow. The benefits of replacing summer fallow with green manures in a rotation need to be further defined for regions with low water availability such as the US Montana plains.

Conclusions

Climate change is a reality. Industrialized countries are more responsible for threat of climate change. Loss wheat production when increased the atmospheric temperature. Increase in temperature along with increase in CO_2 level the reduction of rice and wheat yield. Increased frequency of heat and drought stress, negatively affect crop yields and livestock. Sustainable agricultural systems are needed to produce high-quality and affordable food in sufficient quantity to meet the growing global population need for food, feed, and fuel, and, at the same time, farming systems must have a low impact on the environment. The key agronomical tactics include, but are not limited to diversification of cropping systems, improvement of N fertilizer use efficiency, adoption of intensified rotation with reduced summer fallow, enhancement of carbon conversion from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil, use of reduced tillage in combination with crop residue retention; integration of key cropping practices systematically, and inclusion of N_2-fixing pulses in crop rotations. Integration of these improved farming practices together enables to reduce the use of inorganic fertilizers, increase the system productivity, and lower the carbon footprint. Farmers are increasingly aware that crop production is no longer a yield-income business, and the way the crops are produced will have significant environmental consequences. Over 60 % of the total emissions in food products in grocery stores stem from farm gate raw material. Farmers play a key role in ensuring the provision of low-emission materials to the food chain. There are huge gaps between the development of new cropping technologies and the implementation of the technologies in farming operations. With relevant agro-environmental policies in place, along with the adoption of improved agronomical tactics, increasing food production with no cost to the environment can be achieved effectively, efficiently, and economically.

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