Chapter 1
Greenhouse Gas Emissions and Climate Variability: An Overview

Mukhtar Ahmed

Contents

Abstract A comprehensive overview of greenhouse gas (GHG) emissions of from different sectors across the globe is provide in this chapter. Particular attention is given to agriculture, forestry, and other land use (AFOLU). Since agricultural activities (cultivation of crops, management activities and rearing of livestock) result in production and emissions of GHG, quantification of GHG and its mitigation is addressed in this chapter. The suggested mitigation techniques include the use of bioenergy crops, fertilizer and manure management, conservation tillage, crop rotations, cover crops and cropping intensity, irrigation, erosion control, management of drained wetlands, lime amendments, residue management, biochar and biotechnology. Furthermore, quantification of GHG emissions is discussed using different process based models. These models could further be used as decision support tools under different scenarios to mitigate GHG emissions if calibrated and validated effectively.

Keywords Greenhouse gas emissions • Climate variability • AFOLU • Mitigation

---

M. Ahmed (✉)
Department of Agronomy, Pir Mehr Ali Shah Arid Agriculture University,
Rawalpindi, Pakistan

Department of Biological Systems Engineering, Washington State University,
Pullman, WA, USA
e-mail: ahmadmukhtar@uaar.edu.pk; mukhtar.ahmed@wsu.edu

© Springer International Publishing Switzerland 2017

M. Ahmed, C.O. Stockle (eds.), *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability*,
DOI 10.1007/978-3-319-32059-5_1

1.1 Introduction

Combustion and extensive use of fossil fuels results in the emission of greenhouse gases (GHGs) which contribute to the greenhouse effect. The fundamental phenomenon of greenhouse effect is based upon absorption and transmission of energy, depending upon its wavelength. High temperature bodies such as sun generally emit radiation which is of short wavelength and cooler bodies like earth emit long wavelength radiation. Longer wavelength radiation is called infrared radiation. Infrared radiation is not as harmful according to Planks Quantum theory of radiation energy is inversely proportional to wavelength (ʎ) and directly proportional to frequency (v) i.e. $E=hv$ where $v=c/ʎ$. However, short wavelength radiation easily passes through glass then after striking colder bodies such it is transmitted back at a longer wavelength, which is blocked by the glass resulting in an increased temperature under the glass. This phenomenon is largely used in the greenhouse industry to let solar radiation in and block longer wavelength radiation to increase inside temperature for plant growth even if the outside temperature is too low to grow plants. Some atmospheric gases have the same property and maintain earth's temperature at a certain level. These gasses are called GHGs, and they include carbon dioxide (CO_2), methane (CH_4), water vapor and oxides of nitrogen (NO_X). However, due to intensive use of fossil fuels, industrialization, deforestation and mechanization in agriculture the amount of these GHGs, particularly CO_2, has increased significantly resulting in global warming. The Global Warming Potential (GWP) is used as a measure of the global warming impacts of different GHGs. It is measure of how much energy the emission of one ton of gas will absorb in a particular time period in comparison to one ton of CO_2. The larger the GWP, the greater will be the impact of that gas in comparison to CO_2 over a given time period, i.e., 100 years. GWP allows policy makers to compare emissions and design reduction strategies. Since CO_2 is used as reference it has GWP of 1 while methane (CH_4) GWP is 28–36, nitrous Oxide (N_2O) has a GWP 265–298. High GWP gases, called fluorinated gases, have GWPs in range of the thousands or tens of thousands.

Carbon dioxide is the chief GHG emitted through human activities. The emission of CO_2 has increased significantly due to deforestation which resulted in an alteration of the carbon cycle. Since forests are a main sink for CO_2, their destruction results in increased atmospheric CO_2 (NRC 2010). The increase of carbon dioxide in the atmosphere is due to the burning of fossil fuels. Methane (CH_4) is the second dominant GHG emitted by human activities. The main source of methane is raising of livestock, rice paddies and bacterial action on landfills and wastes. The petrochemical industry and coal mines are also big contributors of methane. In general 35 % of the methane emissions are natural, and 65 % are due to human activities. Nitrous oxide (N_2O), another GHG, is naturally present in the atmosphere due to the N-cycle but it also comes from human activities such as agriculture, transportation, and industry (EPA 2010). Nitrous oxide is the main precursor of ozone depletion. Nitrous oxide emissions from natural lands is 55 % of global N_2O emissions. Kim et al. (2013) concluded that nitrous oxide emissions from natural land is lowerer than from agricultural land. Fluorinated gases are the longest lasting and most potent GHGs destroying ozone layer. GHG emission is now a critical topic due to its devastating effect on different sectors of life, which also results in global warming (Kennedy et al. 2009).

The countries that emited the highest amount of GHG include China (23 %), USA (19 %), the European Union (13 %), India (6 %), the Russian Federation (6 %), Japan (4 %), and Canada (2 %) while other countries produced 28 % (IPCC 2007). Global GHG emissions and sinks are related mainly to land use change. The maximum emission of CO_2 globally is due to deforestation, particularly in Africa, Asia, and South America. According to Houghton et al. (2012) net flux of carbon from land use and land cover change (LULCC) accounted for 12.5 % of anthropogenic carbon emissions. Hergoualc'h and Verchot (2014) studied land use change in Southeast Asia where tropical peat swamp forests are located. These forests act as global carbon stores but due to their intensive degradation and conversion to agricultural lands GHG emission in the region have increased significantly. The major driver of environmental change and increased GHG emissions is land use change(LUC) (Turner et al. 2007; Lambin and Meyfroidt 2011; IPCC 2013). Similarly, it leads to alteration in soil organic carbon and changes in biodiversity (Sala et al. 2000). Therefore, there is a dire need to mitigate the impact of LUC through utilization of renewable energy technologies. Similarly, in order to minimize GHG emissions from land use change, quantification of the direct impact of land use change on GHG emissions is important in order to design adaptation strategies. Meta-analysis is a robust statistical method of identifying trends and patterns in the effects of LUC on GHG emissions. Similarly, different approaches like basic estimation equations, models, field measurements, inference and a hybrid equation approach could be used used to estimate GHG emission (IPCC 2013). Harris et al. 2015. used meta-analysis to quantify the impact of LUC on GHG emissions. Greenhouse gas (GHG) emission factors for iLUC are proposed for inclusion into carbon footprints (CF) of biofuels (NRC 2010). LCA is a good tool for quantifying environmental impacts throughout the life cycle of a product. LCA, when applied to agriculture or forestry products, can include upstream (extraction and production of material inputs e.g. fuels, fertilizers) and downstream impacts (use and disposal by the end consumer). If we consider the LCA for a grain product it will include emissions from synthetic fertilizer production and N_2O emissions from fertilizer application (upstream impacts) and emissions from grain transportation, storage, processing, use, and disposal (downstream impacts) (Kennedy et al. 2009). Greenhouse gas fluxes from a managed ecosystem were elucidated by Paustian et al. (2006). The main processes involved are photosynthesis, respiration, decomposition, nitrification, denitrification, enteric fermentation and combustion. These processes govern the carbon and nitrogen dynamics in soil which could be affected by physical and biological processes. The biological processes include microbial as well as animal and plant activity while physical process include combustion, leaching and runoff. (Fig. 1.1)

Davies-Barnard et al. (2014) concluded that land cover has a significant impact on climate and it is significantly affected by agricultural land use. Agricultural and forestry activities and land-use change are responsible for in one third of GHG

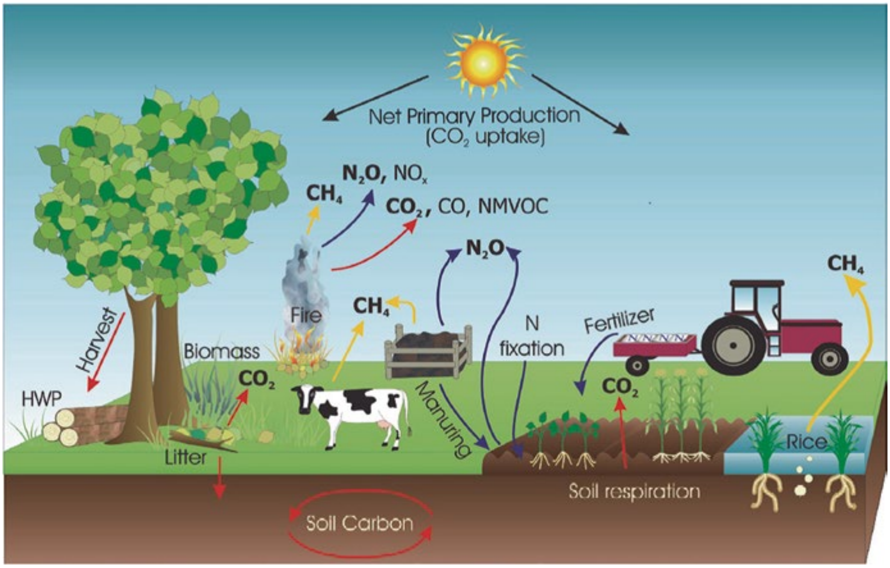

Fig. 1.1 Greenhouse gas emission sources/removals and processes in managed ecosystems (where NMVOC; non-methane volatile organic compounds) (Source: Paustian et al. (2006)

emissions. Agriculture is the dominant land use activity and contributes 5.1–6.1 $GtCO_2$-eq/year (10–12 % of total global anthropogenic emissions of GHGs). N_2O and CH_4 contributions from agriculture are 60 and 50 % respectively. However, these agricultural emissions can be linked to particular crop or animal products (IPCC 2013). The emissions produced by agriculture do not take place at the field level only. There can be spatial dislocation of emissions in which products of agriculture can be transported to another place and utilized there. Similarly, temporal dislocation is the decaying of crop residues over a longer period of time and its later utilization as fuel. The other important source of GHG emissions is the energy sector. The generation and usa of energy results in large emissions of GHGs. Generally more attention of GHG emissions from the energy sector has been given to energy production rather than energy utilization as household electric and electronic equipment (e-products).

Climate change is a major threat to agriculture and food security. GHG emissions from agriculture continue to rise. In order to identify opportunities for reducing emissions while addressing food security, collection of emissions data is necessary to design resilience and rural development goals. FAOSTAT emissions database could be used to estimate GHG emissions from a target regions as it is the most comprehensive knowledge base regarding agricultural greenhouse gas emissions. According to FAOSTAT, (2015) GHG emission (CO_2 equivalent) is continually increasing across the globe (Fig. 1.2). The highest emission is from the agriculture sector followed by land use change. Among continents, Asia is at top with reference to GHG emissions from agriculture followed by America (Fig. 1.2). Greenhouse gase emissions (CO_2 equivalent) from agriculture in Annex I, non-

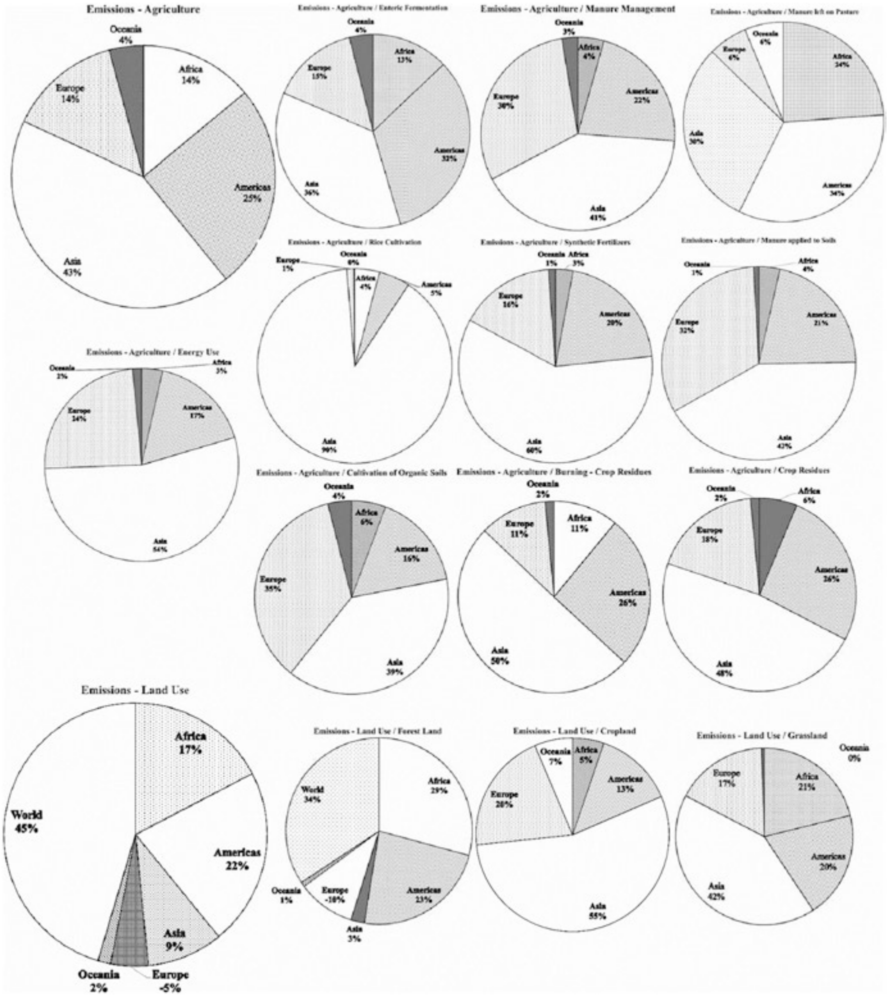

Fig. 1.2 Greenhouse gase (GHG) emissions from agriculture and land use change across the globe

Annex I countries and across the globe provide different pictures in different field of agriculture (Figs. 1.3a and 1.3b). Generally, non-Annex I countries are higher producers of GHGs compared to Annex I countries. Similarly, GHG emissions by sectors involved in agriculture revealed that enteric fermentation contributes the most (40.0 %) to GHG emission while the lowest emissions reported were due to burning crop residues (0.5 %) (FAOSTAT, 2015) (Figs. 1.2, 1.3a and 1.3b). China is the top GHG emitter followed by India. The top ten GHG emitters have been shown in Figs. 1.4a, 1.4b, 1.4c and 1.4d based upon different sectors in agriculture and land use change. FAOSTAT divided GHG emissions under two categories which include agriculture and land use.

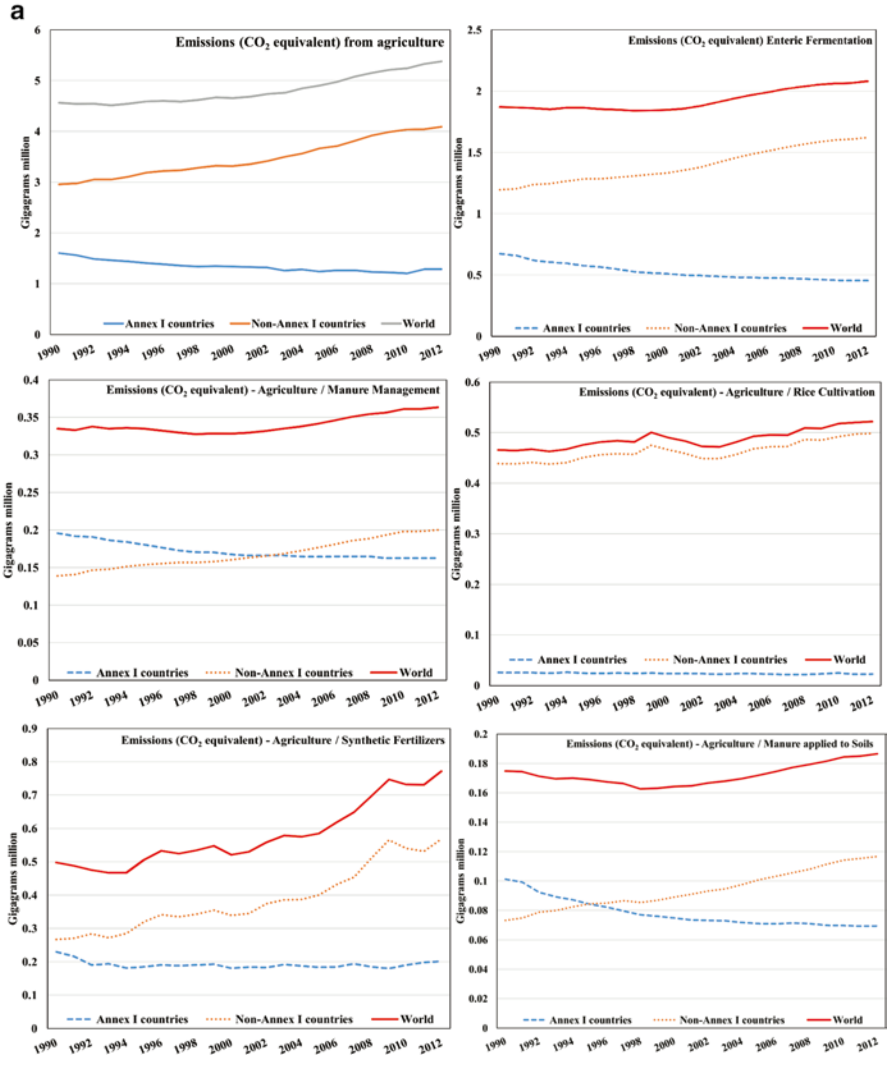

Fig. 1.3a Greenhouse gase (GHG) emissions (CO$_2$ equivalent) from agriculture

GHG emissions could be controlled or minimized by using different techniques including biofuel, fertilizer and manure, conservation tillage, rotations of crops, cover crops, cropping intensity, irrigation, erosion control, drained wetland management, lime amendments, residue management, biochar and biotechnology. Similarly, GHG emissions from rice based cropping systems could be minimized by water and residue management, organic amendments, ratoon cropping, fallow management, use of nitrification and urease inhibitors and by using different fertilizer placement methods and sulfur products. In case of animal production GHGs emissions is mainly because of enteric fermentation, housing and manure management.

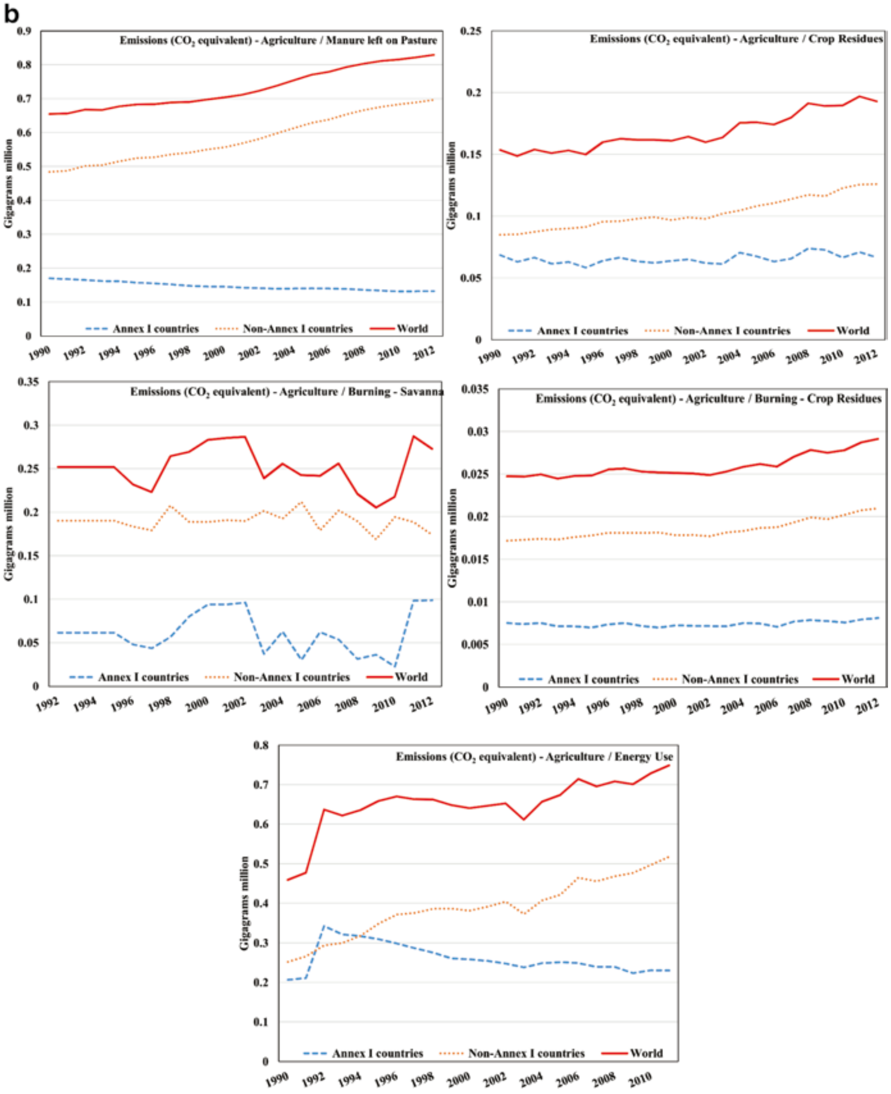

Fig. 1.3b Greenhouse gas (GHG) emissions (CO$_2$ equivalent) from agriculture

GHG emissions from enteric fermentation and housing could be modified by using different methods. It includes management in the feed and use of different microorganism products. However, in case of manure management techniques like anaerobic digestion, liquid manure storage and treatment practices could be used to minimize or modify GHG emissions.

Forestry has considerable potential to mitigate GHG emissions through the sequestration and storage of forest carbon stocks. Various forestry activities have potential to reduce GHG emissions. According to Morgan et al. (2010) agroforestry

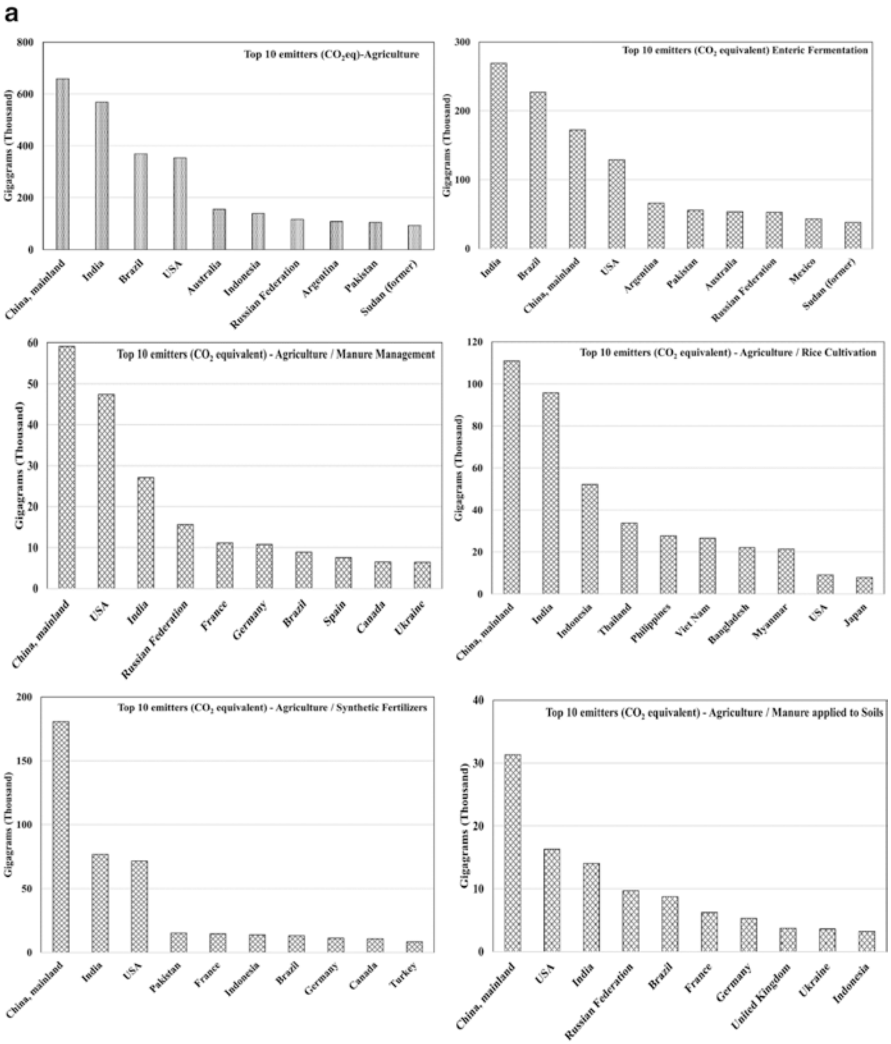

Fig. 1.4a Top 10 greenhouse gase (GHG) emitters (CO_2 equivalent) from agriculture

could contribute to carbon sequestration, GHG mitigation, and adaptation to shifting climate. Land use change is the main contributor to GHG emissions, therefore, it needs to be managed effectively. Land use change mainly includes three directional processes – afforestation, reforestation and deforestation. The balance among these three processes is important to manage GHG flux. Different methods could be used to estimate GHG fluxes from LUC. The GHG flux linked with LUC is the sum of the GHG fluxes from previous land use categories plus the sum of the GHG fluxes related to the current land use (IPCC 2007). Equations 1 and 2 could be used to study annual carbon stock changes for LUC estimates as the sum of changes in all land use categories (Dokoohaki et al. 2016).

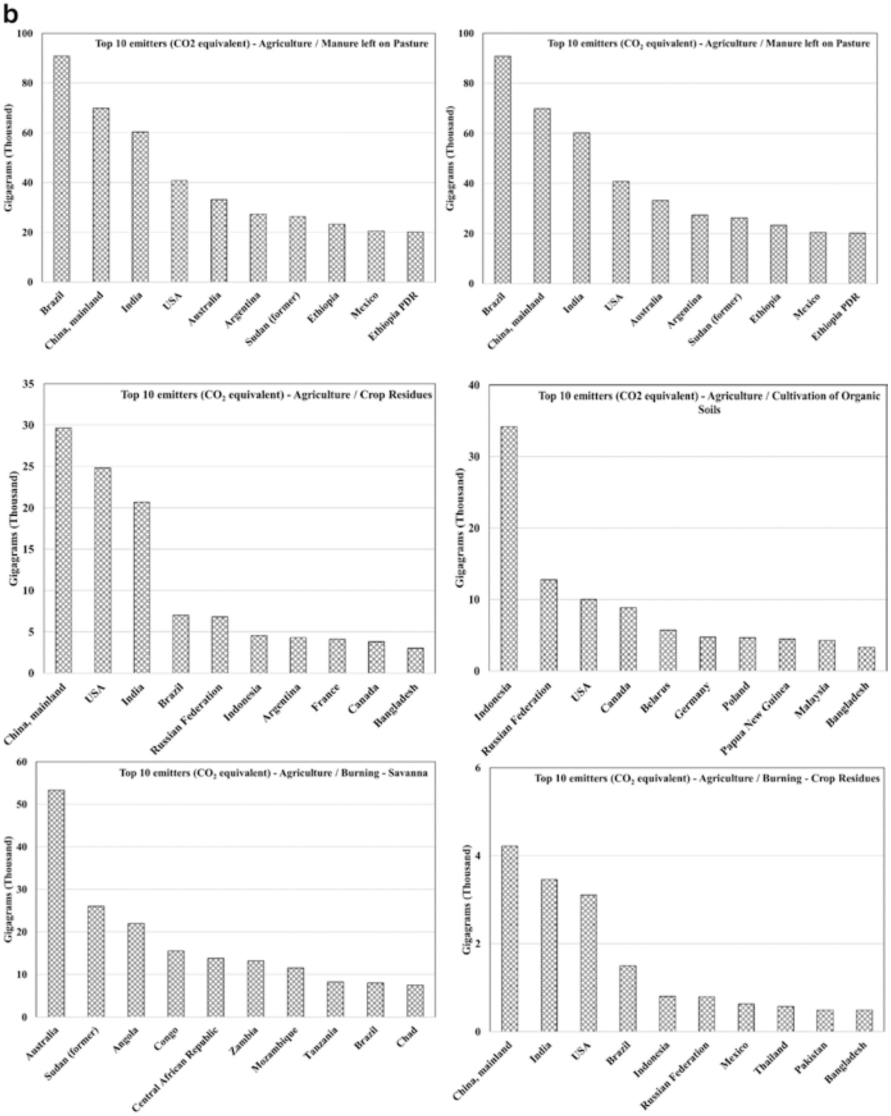

Fig. 1.4b Top 10 greenhouse gase (GHG) emitters (CO$_2$ equivalent) from agriculture

$$\Delta C_{luc} = \Delta C_{luco} + \Delta C_{lucn} \tag{1}$$

$$\Delta C_{luc} = \Delta C_{luc\,fl} + \Delta C_{lu\,cl} + \Delta C_{lu\,gl} + \Delta C_{lu\,wl} \tag{2}$$

where ΔC; carbon stock change (metric tons CO$_2$-eq ha^{-1} year^{-1}), luc; land use change, o; old land use, n; new land use, fl; forest land, cl; crop land, gl; grazing land and wl; wetlands.

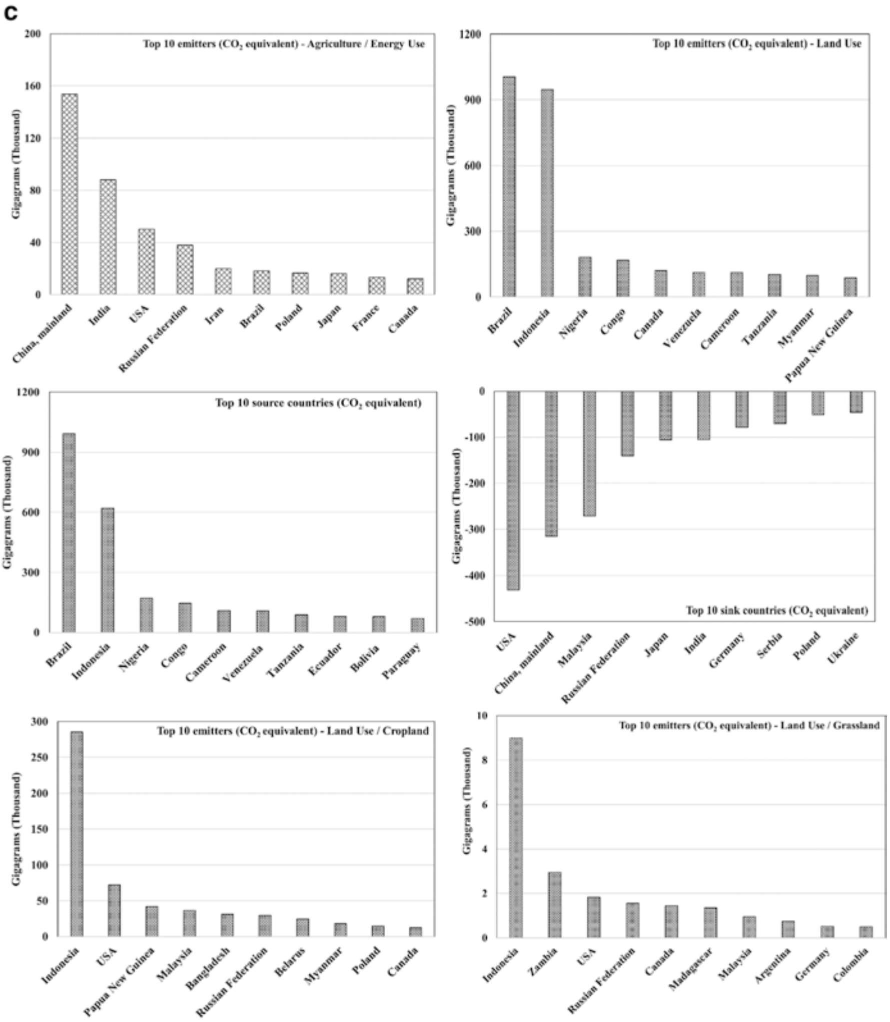

Fig. 1.4c Top 10 greenhouse gase (GHG) emitters (CO_2 equivalent) from agriculture and land use change

The annual carbon stock exchange for a particular section e.g. management regime could be calculated by the following equation

$$C_{luc} = \sum_{i}^{n} \Delta Cluci \tag{3}$$

where ΔCluc; carbon stock changes for a land use change and i denotes a specific division

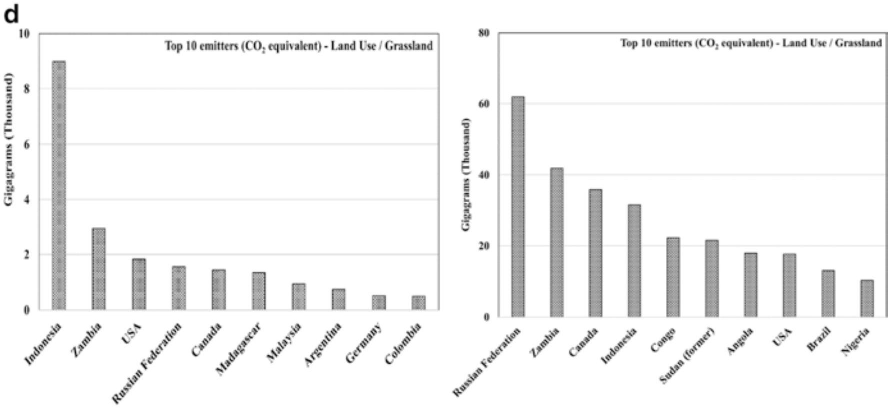

Fig. 1.4d Top 10 greenhouse gase (GHG) emitters (CO_2 equivalent) from agriculture and land use change

Many forest and agricultural lands have live/dead biomass carbon stocks (LDBCS) and soil organic carbon which acts as a good carbon store. The following equation (Dokoohaki et al. 2016) could be used to estimate the annual change in carbon stocks in dead wood due to land conversion.

$$\Delta C_{dom} = \left(C_n - C_o\right) \times A_{on} \div T_{on} \tag{4}$$

where ΔC_{dom} = annual change in carbon stocks in dead wood or litter (metric tons C year^{-1}), C_o = dead wood/litter stock, under the old land-use category (metric tons C ha^{-1}); C_n = dead wood/litter stock, under the new land-use category (metric tons C ha^{-1}), A_{on} = area undergoing conversion from old to new land-use category (ha), T_{on} = time period of the transition from old to new land-use category (year) (The default is 20 years for carbon stock increases and 1 year for carbon losses.)

Soil organic carbon stock (SOCS) is also influenced by land use change. The significant change in SOCS occurs due to conversion of land to crop land (Six et al. 2000). Aalde et al. (2006) proposed a method to estimate changes in SOCS from mineral soils.

$$\Delta C_{mineral} = \left[\left(SOC_f - SOC_i\right) \times CO_2 MW\right] \div D \tag{5}$$

where $\Delta C_{mineral}$ = annual change in mineral SOCS (metric tons CO_2-eq year^{-1}), SOC_f = soil organic carbon stock at the end of year 5 (metric tons C), SOC_i = soil organic carbon stock at the beginning of year 1 (metric tons C), CO_2MW = ratio of molecular weight of CO_2 to C (44/12 dimensionless) and D = time dependence of stock change factors (20 years).

Simialrly, SOCS from mineral soils could be calculated by using the following equation (Aalde et al. 2006)

$$SOCS = SOC_{ref} \times F_{lu} \times F_{mg} \times F_i \times A \tag{6}$$

where SOCS = soil organic carbon stock at the beginning ($SOCS_i$) and end of the 5 years ($SOCS_f$) (metric tons C), SOC_{ref} = reference soil organic carbon stock (metric tons C ha^{-1}), F_{lu} = stock change factor for land use (dimensionless), F_{mg} = stock change factor for management (dimensionless), F_i = stock change factor for input (dimensionless) and A = area of land-use change (ha).

Uncertainty analysis is an important technique to quantify the uncertainty of greenhouse gas (GHG) emissions from different sectors. It can help policy makers and farmers decide management options to minimize GHG emissions based upon an uncertainty range. If uncertainty for an estimate is low farmers can invest in that management practices as it has high probability of GHG emission reduction. A Monte Carlo approach is a comprehensive, sound method that could be used for estimating the uncertainty. *Greenhouse Gas Emissions and Climate Variability: An Overview* covers the GHG emission status by different sectors and how it could be mitigated by using different practices in agriculture and land use sectors. This chapter reviews available methods for studying/quantifying GHG emission for accurate design of strategies to address the issue of climate variability.

1.2 Greenhouse Gas Emission and Climate Variability

Climate variability is one of the burning issues in all fields from social sciences to the applied sciences. Climate vulnerability threatens global climatic cycles and world food production systems, thus affecting the lives of all people. Most of the world is exposed to the effects of climatic change due to extreme variability in temperature and rainfall. Risk reduction represents a major avenue for responding to existing rise in temperature, carbon dioxide, GHGs, flood and drought hazards. Global warming is the greatest environmental challenge of the twenty-first century as it results in increased average air temperature (Gnansounou et al. 2004). Wu et al. (2010) concluded that cities act as heat islands and since large areas of grassland and forest were converted to barren land resulted in greater climate variability. The guiding principle to reduce climate risks is to minimize GHG emission. In recent decades significant changes in the atmospheric temperature have been observed. The global mean annual temperature at the end of the twentieth century was almost 0.7 °C and it is likely to increase further by 1.8–6.4 °C by the end of this century (IPCC 2007). The warmest decade in the last 300 years was 1990–2000 with the increase of 0.5 °C in comparison to the baseline temperature of 1961–1990. A variety of models ranging from simple models to complex earth system models were used to project future warming under different representative concentration pathways (RCPs). The RCP includes RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (The numbers refer to the rate of energy increase per unit area at the surface of the earth, in watts per square meter). RCP 2.6 is the normal scenario in which a guideline was established to limit global warming to 2 °C (3.6 °F) above the level that existed before industrial times. All other scenarios reflect severe warming due to increasing rates of GHG emission. The scenario RCP 8.5 reflects "business as usual" in which

Table 1.1 Changes in global mean surface temperature in °C and global mean sea level rise in m (bottom) for the two time periods shown, referenced to the baseline period 1986–2005 (The "likely range" gives confidence limits for a 5–95 % interval)

Climate variable	RCP scenario	2046–2065		2081–2100	
		Mean	Range	Mean	Range
Mean temperature change (°C)	RCP2.6	1	0.4–1.6	1	0.3–1.7
	RCP4.5	1.4	09–2.0	1.8	1.1–2.6
	RCP6.0	1.3	0.8–1.8	2.2	1.4–3.1
	RCP8.5	2	1.4–2.6	3.7	2.6–4.8
		Mean	**Range**	**Mean**	**Range**
Mean Sea Level Rise (m)	RCP2.6	0.24	0.17–0.32	0.4	0.26–0.55
	RCP4.5	0.26	0.19–0.33	0.47	0.32–0.63
	RCP6.0	0.25	0.18–0.32	0.48	0.33–0.63
	RCP8.5	0.3	0.22–0.38	0.63	0.45–0.82

no policies are implemented to limit GHG emission. The projected increase in mean temperature and rise in sea level in comparison to baseline (1986–2005) are presented in Table 1.1 (Harris et al. 2015). Climate variability resulted in a change in the intensity and frequency of rainfall which increased flooding and soil erosion.

Crop phenology and productivity will be affected by warmer climates. Craufurd and Wheeler (2009) reported earlier flowering and maturity due to a rise in temperature. Moreover, increased temperature resulted in reproductive failure and yield reductions in many crops. Lobell et al. (2011) reported a 1.7 % reduction in maize yield due to exposure of maize to degree days above 30 °C. Increased night temperature is another effect of GHG which could reduce crop yield. Serious effects have been reported for rice where an increase in night temperature from 27 °C to 32 °C caused 90 % yield reduction (Mohammed and Tarpley 2009). Climate variability can also modify grain quality since high temperature during grain filling affects the protein content of wheat (Hurkman et al. 2009). Pittock (2003) concluded in their findings that the frequency of extreme events will increase due to global warming. Plant processes like photosynthesis will be affected by high temperature which could lead to reduction in growth and yield (Calderini and Reynolds 2000; Talukder et al. 2014; 2013; Wang et al. 2011) (Table 1.2).

A panel of the National Research Council (United States) (2010) on advancing the science of climate change concluded that world mean temperature was 0.8 °C higher during the first decade of twenty-first century compared to first decade of twentieth century. Moreover, they reported that most of the warming was related to CO_2 and other GHGs which can trap heat. The energy sector is the largest contributor to climate change as it involves burning of fossil fuels (coal, oil, and natural gas). Similarly, the panel identified agriculture, forest clearing, and certain industrial activities as big contributors to climate change due to emission of GHGs. Kang and Banga (2013) found that climate change is a well-recognized man made global environmental challenge and that agriculture is significantly influenced by it. Food and Agriculture Organization (FAO) experts reported that each 1 °C rise in temperature would cause annual wheat yield loss of about 6 million tons. However, when

Table 1.2 Impacts of climatic variables on crops with recommended adaptation strategies

Climatic impact	Effect on crop	Adaptation	Reference
Increased temperature (0.67, 0.53, and 0.38 °C decade − 1)	Change in crop life cycle and decreased yield	Adjusting the sowing date, converting tillage system and adopting water-saving technologies	Zhang et al. (2015)
Heat stress	Decreased in number of days to mature (1.8 days for 2025 and by 2.3 days for 2050)	Shift the planting date	Bao et al. (2015)
Increases in precipitation and CO_2 concentration	Soybean projected yield increase from 6 to 22 % for 2025 and 8 to 35 % for 2050 for rainfed conditions.		
El Niño–Southern Oscillation (ENSO)	Might influence growth, maturity, and yield of winter wheat	Shift planting date and cultivar selection	Woli et al. 2014
Temperature	Modification in flowering time of wheat	Use longer-season wheat varieties and varieties with increased heat-stress resistance	Wang et al. 2015
Climate extremes (temperature and precipitation)	Change in rainfed crop yields	Irrigation	Troy et al. 2015
Heat stress	Reproductive growing duration (RGD) and yield	Shifts in cultivars	Tao et al. 2015
Heat stress	Yield losses due to increased frequency and magnitude of heat stress	Heat-tolerant ideotypes	Stratonovitch and Semenov 2015
Elevated temperature	Alteration in the phenology of crops	Agronomic and breeding solutions	Sadras et al. 2015
Reduction of annual precipitation and an increase of air temperature	Shortening of growing season	Supplemental irrigation	Saadi et al. 2015
Higher temperatures	Shortening of the grain filling period, reduce crop yields		Rezaei et al. 2015

losses of all other crops were taken into consideration it might cause loss of US$ 20 billion each year (Swaminathan and Kesavan 2012). Climate variability can reduce crop duration, disturb source sink relationships, increase crop respiration, affect survival and distribution of pest populations, accelerate nutrient mineralization and decrease nutrient use efficiency. It can also lead to changes in the frequency and intensity of drought and floods (Sharma and Chauhan 2011). Overall agricultural production will be significantly affected by climate variability which will influence food security.

1.3 Greenhouse Gas Mitigation and Climate Change Adaptation

Climate change is one of the complex burning issues currently faced by the world. Greenhouse gases are trapping heat energy which results in global warming. It has been reported earlier that if GHGs are stopped completely, climate change will still affect future generations. Therefore, we need to show a high level of commitment to tackle the issue of climate change. Mitigation and adaptation are two approaches used to respond to climate change. Mitigation involves reducing and stabilizing the levels of GHGs while adaptation is adapting to climate change using different techniques. Mitigation is possible by finding ways by which we can increase sinks for GHGs. Mainly the sinks includes forests, soil and oceans, therefore it is necessary to manage those resources which can absorb GHGs. According to Calvin et al. (2015) around 40 % of GHG emissions are from agriculture, forestry, and other land use (AFOLU). Their work further elaborated that implementation of climate policy is necessary to minimize GHG emissions. A multi-model comparison approach was used to study the future trajectory of AFOLU GHG emissions with and without mitigation. a similar approach about the role of land for the mitigation of AFOLU GHG emissions was earlier reported which includes the use of bioenergy crops (Calvin et al. 2013). The models used were Applied Dynamic Analysis of the Global Economy (ADAGE) (Ross 2009.); MIT Emissions Prediction and Policy Analysis (EPPA) (Paltsev et al. 2005); GCAM (Global Change Assessment Model) (Calvin et al. 2011) and TIAM-WORLD (Loulou 2008). The results indicated larger uncertainties in both present and future emissions with and without climate policy.

Bioenergy crops are the biggest potential source that could be used to minimize GHG emissions. Hudiburg et al. (2015) proposed perennial grasses as effective bioenergy crops on marginal lands. They evaluated the DayCent biogeochemical model in their studies and concluded that the model predicted yield and GHG fluxes with good accuracy. They found that with the replacement of traditional corn-soybean rotation with native prairie, switchgrass, and Miscanthus resulted in net GHG reductions of 0.5, 1.0 and 2.0 Mg C ha^{-1} $year^{-1}$ respectively. Since bioenergy crops have the potential to mitigate climate change impacts, they have been under consideration for the past decade. However, these bioenergy crops could only be grown on marginal lands as most of the world land is occupied by major food crops. Albanito

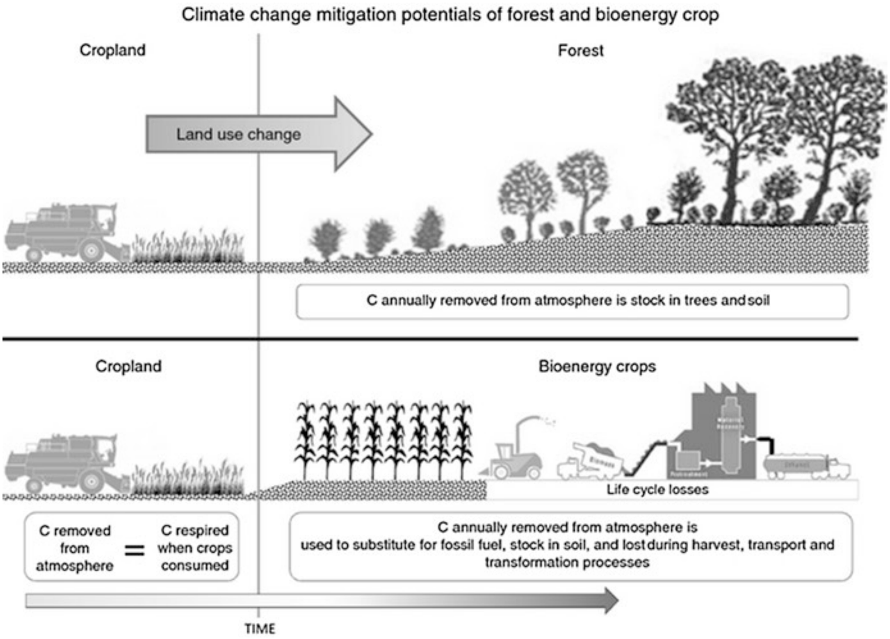

Fig. 1.5 Carbon implications of converting cropland to forest or bioenergy crops for climate mitigation: a global assessment (Source: Albanito et al. 2016)

et al. (2016) reported C4 grasses (Miscanthus and switch-grass) as the potential bioenergy crops with the highest climate mitigation potential. These crops would displace 58.1 Pg of fossil fuel C equivalent (C_{eq} oil) if the proposed land use change took place. Similarly, woody energy crops (poplar, willow and Eucalyptus species) could displace 0.9 Pg C_{eq} oil under proposed land use change. The best climate mitigation option is the afforestation of suggested cropland which would sequester 5.8 Pg C in biomass in the 20-year-old forest and 2.7 Pg C in soil. Croplands could not accumulate carbon for more than a year therefore, in order to mitigate climate change, agricultural lands should either be converted to forest land or bioenergy production (Fig. 1.5). Food security will be a big challenge in the future as the world population will be 9–10 billion by 2050. Therefore, bioenergy crops could not come at the expense of food crops. Earlier researchers accepted the potential of biomass energy production but according to them it was not enough to replace just a few percent of current fossil fuel usage. Increasing biomass energy production beyond a certain level might imperil food security and worsen condition of climate change (Field et al. 2008). However, biomass proponents are recommending the use of grasslands and marginal crop lands as potential sites for bioenergy crops (Qin et al. 2015; Slade et al. 2014). Furthermore, Qin et al. (2015) suggested Miscanthus as the best potential crop to mitigate GHGs emissions on marginal lands compared to switchgrass. Biomass and ethanol yield were higher in Miscanthus. Coyle (2007) concluded that different crops, e.g. corn, sugarcane, rapeseed and soybean could be

Table 1.3 Energy potential from biofuel crops using current technologies and future cellulosic technologies

FT	FM (Mt $year^{-1}$)	GBC (GJ/ton)	GBE (EJ $year^{-1}$)	NEBR (Output/Input)	NBE (EJ $year^{-1}$)	Refs
Corn kernel	696	8	5.8	1.25	1.2	Hill et al. 2006
Sugar cane	1324	2	2.8	8	2.4	IEA 2004
Cellulosic biomass	–	6	–	5.44	–	Farrell et al. 2006
Soy oil	35	30	1	1.93	0.5	Worldwatch 2006
Palm oil	36	30	1.1	9	1	Worldwatch 2006
Rape oil	17	30	0.5	2.5	0.3	IEA 2004

Source: Field et al. (2008)

Where *FT* Feedstock type, *FM* Feedstock mass, *GBC* Gross biofuel conversion (Useful biofuel energy per ton of crop for conversion into biofuel ($1GJ = 10^9$ J)), *GBE* Gross biofuel energy (Product of feedstock mass and gross biofuel conversion ($1EJ = 10^{18}$ J)), *NEBR* Net energy balance ratio (Ratio of the energy captured in biomass fuel to the fossil energy input) and *NBE* Net biofuel energy (Energy yield above the fossil energy invested in growing, transporting and manufacturing, calculated as gross biofuel energy × (net energy balance ratio −1)/net energy balance ratio)

used to produce biofuel. Energy potential from different feedstocks have been presented in Table 1.3.

Chum et al. (2011) considered bioenergy as a good renewable source for energy. Bioenergy can easily replace fossil fuels and minimize GHG emissions (Dornburg and Faaij 2005; Dornburg et al. 2008; 2010). Implementation of all these techniques requires identification of terrestrial ecosystems which could contribute to climate mitigation. Many countries have announced different targets to substitute fossil fuels with biofuels (Ravindranath et al. 2008). Table 1.4 shows that C4 bioenergy crops have higher cumulative carbon mitigation potential than SRCW. However, this mitigation potential changes across the continents as in Oceania, SRCW produced higher C savings than energy crops. According to Albanito et al. (2016) cumulative carbon strength due to reforestation is highest in Asia, followed by Africa, North and Central America, South America, Oceania and Europe. However, on a per hectare basis C sequestration strength is higher in South America followed by North and Central America, Oceania, Asia, Africa and Europe. Among climatic regions, warm-dry climates could save 44.7 % of the C in forest followed by warm-moist (42.6 %), cool-dry (11.3 %) and cool-moist (1.4 %) regions (Table 1.5).

Biochar also has potential to mitigate climate change by sequestering carbon. Biochar use improved soil fertility, reduced fertilizer inputs, GHG emissions, and emissions from feedstock, enhanced soil microbial life and energy generation. Its use also increased crop yield. (Woolf et al. 2010) reported that biochar use could minimize GHG emissions by 12 %. The concept of sustainable use of biochar is presented in Fig. 1.6 as proposed by (Woolf et al. 2010). Photosynthesis is a carbon reduction processes in which plants produce biomass by using atmospheric CO_2. Residues from crops and forests were subjected to the process of pyrolysis which produced bio-oil, syngas, process heat and biochar (output). These outputs serve as a good source of energy which could minimize GHG emissions. Furthermore, bio-

Table 1.4 Land use change C mitigation potential

Land use	CR	TCM	CMB	CSSS	ALD
C4 Bioenergy crops	Asia	27.62	24.06	3.56	66.07
	Africa	8.58	7.69	0.89	61.23
	Europe	10.86	7.74	3.12	123.21
	North America	10.49	8.89	1.6	74.34
	South America	10.71	9.58	1.13	58.08
	Oceania	0.19	0.16	0.03	1.98
Forest	Asia	3.84	2.73	1.11	94.52
	Africa	1.56	1.11	0.44	42.31
	Europe	0.31	0.17	0.15	9.97
	North America	1.47	0.96	0.5	24.67
	South America	0.74	0.41	0.34	6.27
	Oceania	0.51	0.39	0.12	8.7
Short Rotation Coppice Woody (SRCW) crops	Asia	0.48	0.2	0.28	10.49
	Africa	0.0045	0.0019	0.0026	0.35
	Europe	0.92	0.52	0.41	12.54
	North America	0.18	0.1	0.07	2.38
	South America	0.03	0.03	0.01	0.46
	Oceania	0.01	0.01	0	0.13

Source: Albanito et al. (2016)

Where *CR* Continental region, *TCM* Total C mitigated, *CMB* C mitigated from biomass use/increment (Pg C forest and Pg Ceq oil for bioenergy crops), *CSSS* C stock sequestered in soil (Pg C) and ALD; Agricultural land displaced (Mha)

char could also be used to improve agricultural soils (Fig. 1.6). Roberts et al. (2009) suggested biochar (biomass pyrolysis) as a good source to mitigate climate change and minimize fossil fuel consumption. They used life cycle assessment (LCA) to estimate the impact of biochar on energy and climate change and concluded that biochar resulted in negative net GHG emissions. However, the economic viability of biochar production depends upon the cost of feedstocks. Similarly, a well-to-wheel (WTW) LCA model was developed to assess the environmental profile of liquid fuels through pyrolysis (Kimball 2011). Bruckman et al. 2014 reported biochar as a potential geoengineering method to mitigate climate change and design adaptation strategies. Biochar as a soil amendment can sequester C and it is a useful option to mitigate climate change (Hudiburg et al. 2015). Biochar stability and decomposition are the best criteria to evaluate its contribution to carbon (C) sequestration and climate change mitigation. (Macleod et al. 2015) reported that around 97 % of biochar contributes directly to C sequestration in soil. Similarly, the biochar effect on soil organic matter (SOM) dynamics depends upon characteristics of biochar and

Table 1.5 Land use change C mitigation potential across global climatic regions

Land use	CR	TCM	CMB	CSSS	ALD
C4 Bioenergy crops	CD	1.69	0.84	0.85	32.47
	CM	18.06	13.94	4.12	176.74
	WD	0.1	0.08	0.02	2.2
	WM	48.59	43.26	5.33	273.49
Forest	CD	0.95	0.59	0.36	47.38
	CM	0.12	0.04	0.08	2.67
	WD	3.77	2.84	0.93	90.96
	WM	3.6	2.3	1.3	45.44
Short Rotation Coppice Woody (SRCW) crops	CD	0.42	0.06	0.36	13.53
	CM	1.05	0.68	0.38	10.37
	WD	0.01	0.01	0.01	0.85
	WM	0.14	0.12	0.02	1.6

Source: Albanito et al. (2016)
Where *CR* Climate region, *TCM* Total C mitigated, *CMB* C mitigated from biomass use/increment (Pg C forest and Pg Ceq oil for bioenergy crops), *CSSS* C stock sequestered in soil (Pg C), *ALD* Agricultural land displaced (Mha), *CD* Cool-Dry, *CM* Cool-Wet, *WD* Warm-Dry and *WM* Warm moist

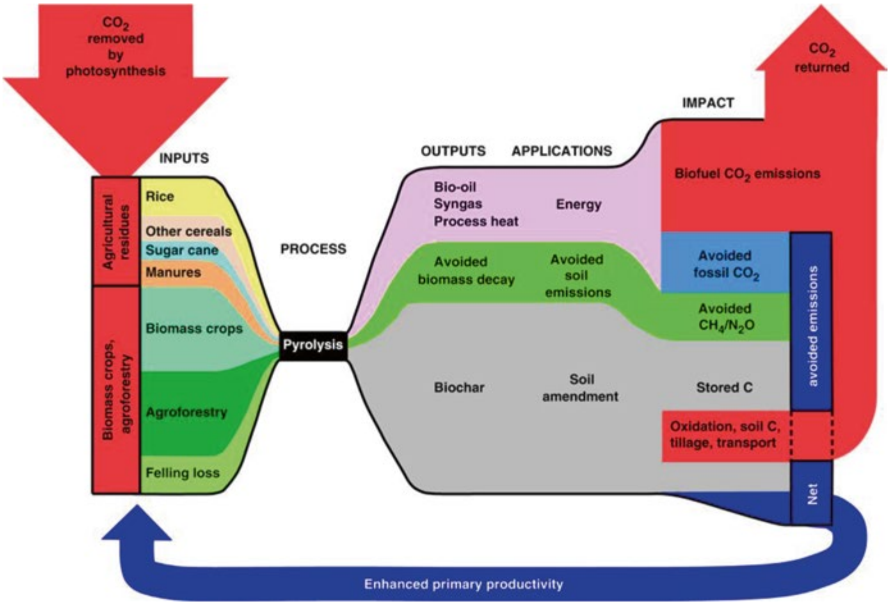

Fig. 1.6 Sustainable biochar concept (Source: Woolf et al. 2010)

soils. Nitrous oxide (N_2O), which is the main GHG coming from agricultural soil, could be minimized by biochar amendment (Ignaciuk 2015). All of these findings support the potential of biochar to be used as a climate change mitigation strategy.

1.4 Modeling and Simulation (Models Used in GHGE Studies)

Quantification of GHG emissions is made possible by the use of process based models. These models could further be used as decision support tools under different scenarios to mitigate GHG emissions. Models should complement field trials in order to have realistic assessments of bioenergy crop production on GHG emissions. The results obtained from simulation studies are sufficiently authentic when validated with field data. Used properly, models could be used to quantify GHG emissions. Models used in GHG studies include CENTURY (Bennetzen et al. 2015), RothC (Albanito et al. 2016), EPIC (Williams 1995; Izaurralde et al. 2006), SOCRATES (Smith 2015), C-Farm (Calvin et al. 2015), ECOSSE (Hill et al. 2006) CropSyst (Stöckle et al. 2003), ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) (Nayak et al. 2015), DNDC (DeNitrification DeComposition) (Zhang et al. 2016), ECOSYS (Frank et al. 2015), HOLOS (Wei et al. 2015), DSSAT (Jones et al. 2003) and STICS (Brisson et al. 1998; 2003). The DAYCENT process based model estimates soil organic carbon on daily basis. It also has the potential to simulate GHG fluxes (N_2O, NOx, and CH_4) for terrestrial ecosystems (Kalafatis et al. 2015) (Table 1.6).

Quantification of GHG emissions is the first step to design mitigation strategies for climate change. Beside these process based models, different publically-accessible tools are also available which could be used to quantify GHG emissions. The calculators include Agri-LCI models, C-PLAN, Carbon Footprint Calculator, DNDC calculator, FarmGAS, Fieldprint Calculator and HOLOS. Similarly, among process based models it is essential to use those models that have low uncertainty. Ogle et al. (2007) reported that simulation modelling is useful to estimate C sequestration and to mitigate GHG emissions under different agricultural managements. However, these models are not accurate enough to simulate C dynamics under different agroecosystems which leads to uncertainty in the results. Quantification of uncertainty is important to confirm the accuracy of models. Uncertainty analysis either uses Monte Carlo Analyses or linear mixed-effects models (empirically based methods). Knightes and Cyterski (2005) suggested comparison between observed and simulated values as good criteria for the evaluation of model performance. This empirically based method was considered a robust estimate of uncertainty (Fig. 1.7a). It is in contrast with error propagation methods (Monte Carlo approach) in which uncertainty is quantified by probability distribution functions. It requires multiple results to obtain approximate confidence intervals for a model estimate (Fig.1.7b). Monte Carlo Analysis could not be used on CENTURY which has too many parameters (Ogle et al. 2007). Webster et al. (2002) concluded that evaluation of uncertainty was important to have accurate prediction from models.

Table 1.6 Use of processes based models in Greenhouse Gases (GHG) studies

Models	Application	References
APSIM	N_2O fluxes	Chum et al. (2011)
CropSyst	Climate change, Estimate long-term soil organic carbon, annual N_2O soil emissions and N balance	Farrell et al. 2006; Ogle et al. 2003; Ipcc 2011
CENTURY	Soil organic carbon (SOC) dynamics in wheat-corn cropping systems	Qin et al. 2015
ECOSSE	Simulate soil C dynamics and GHG emissions	Hill et al. 2006
DSSAT	Irrigation and GHG emissions, GHG emissions reduction potentials	Cardozo et al. 2015; Reddy 2015
DNDC and DayCent	Estimation of nitrous oxide	Calvin et al. 2013; Loulou 2008; Ravindranath et al. 2008
DayCent	Estimation of soil GHG using inverse modelling parameter estimation software (PEST)	Daioglou et al. 2015
DayCent	Estimation of potential of switchgrass (*Panicum virgatum* L.) as bioenergy crop	Paltsev et al. 2005
DayCent	Calibration of model using inverse modeling approach	Ross 2009
DayCent	Studying GHG emissions under different cropping systems	Calvin et al. 2011
EPIC	C dynamics	Izaurralde et al. 2006
RothC	SOC sequestration with the introduction of cover crops	IEA 2004
STICS	Nitrate leaching, N and water dynamics	Dornburg et al. 2008; Constantin et al. 2015

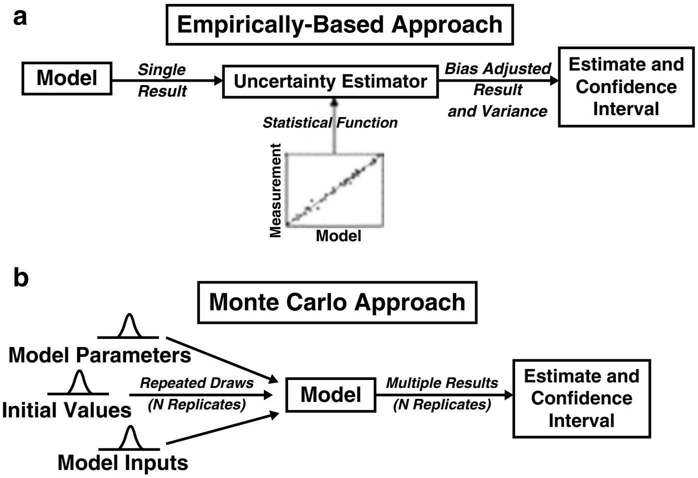

Fig. 1.7 Conceptual diagram with the key components for an uncertainty analysis using (**a**) an empirically based vs. (**b**) Monte Carlo approach. (Source: Ogle et al. 2007)

1.5 Conclusion

Greenhouse Gas Emissions and Climate Variability: An overview elaborated that in order to minimize GHG emissions we need to first accurately estimate GHG emission using different approaches like LCA. Second, after quantification, different mitigation approaches, like changes in land use, should be adopted by considering different factors. Albanito et al. (2016)) suggested bioenergy cropping as the best mitigation strategy under a changing climate. Meanwhile biochar also has potential to mitigate climate change by sequestering carbon. Woolf et al. (2010) proposed the concept of sustainable use of biochar. Different process based models could be used to accurately estimate GHG emissions in response to different land management. These models could be finally used as decision support tools to mitigate climate change. However, in order to utilize these models as effective decision support tools, the use of uncertainty analysis is of utmost importance.

References

Aalde, H., P. Gonzalez, M. Gytarsky, T. Krug, W. Kurz, R.D. Lasco, D. Martino, B. Mcconkey, S. Ogle, and K. Paustian. 2006. Generic methodologies applicable to multiple land-use categories. *IPCC Guidelines for National Greenhouse Gas Inventories,* 4. Institute for Global Environmental Strategies (IGES), Hayama, Japan.

Albanito, F., T. Beringer, R. Corstanje, B. Poulter, A. Stephenson, J. Zawadzka, and P. Smith. 2016. Carbon implications of converting cropland to bioenergy crops or forest for climate mitigation: A global assessment. *GCB Bioenergy* 8: 81–95.

Bennetzen, E.H., P. Smith, and J.R. Porter. 2015. Decoupling of greenhouse gas emissions from global agricultural production: 1970–2050. *Global Change Biology* 22: 763–781.

Brisson, N., C. Gary, E. Justes, R. Roche, B. Mary, D. Ripoche, D. Zimmer, J. Sierra, P. Bertuzzi, P. Burger, F. Bussière, Y.M. Cabidoche, P. Cellier, P. Debaeke, J.P. Gaudillère, C. Hénault, F. Maraux, B. Seguin, and H. Sinoquet. 2003. An overview of the crop model stics. *European Journal of Agronomy* 18: 309–332.

Brisson, N., B. Mary, D. Ripoche, M.H. Jeuffroy, F. Ruget, B. Nicoullaud, P. Gate, F. Devienne-Barret, R. Antonioletti, C. Durr, G. Richard, N. Beaudoin, S. Recous, X. Tayot, D. Plenet, P. Cellier, J.-M. Machet, J.M. Meynard, and R. Delécolle. 1998. STICS: A generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* 18: 311–346.

Bruckman, V.J., M. Klinglmüller, B.B. Uzun, and E. Apaydin-Varol. 2014. *Potentials to mitigate climate change using biochar–the Austrian perspective*. Potentials to mitigate climate change using biochar. IUFRO Occasional Papers 27.

Calderini, D.F., and M.P. Reynolds. 2000. Changes in grain weight as a consequence of de-graining treatments at pre- and post-anthesis in synthetic hexaploid lines of wheat (<i>Triticum durum</i>x<i>T. tauschii). *Functional Plant Biology* 27: 183–191.

Calvin, K., L. Clarke, J. Edmonds, J. Eom, M. Hejazi, S. Kim, P. Kyle, R. Link, P. Luckow and P. Patel. 2011. *GCAM Wiki documentation* [Online]. Available: https://wiki.umd.edu/gcam/index.php/Main_Page [Accessed].

Calvin, K., M. Wise, D. Klein, D. Mccollum, M. Tavoni, B. Van Der Zwaan, and D.P. Van Vuuren. 2013. A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO2 emissions reduction. *Climate Change Economics* 04: 1340014.

Calvin, K. V., R. Beach, A. Gurgel, M. Labriet and A.M. Loboguerrero Rodriguez. 2015. Agriculture, forestry, and other land-use emissions in Latin America. *Energy Economics* 56, May 2016: 615–624.

Cardozo, N.P., R. De Oliveira Bordonal, and N. La Scala Jr. 2015. Greenhouse gas emission estimate in sugarcane irrigation in Brazil: Is it possible to reduce it, and still increase crop yield? *Journal of Cleaner Production* 112: 3988–3997.

Chum, H., A. Faaij, and J. Moreira. 2011. Bioenergy. In *IPCC special report on renewable energy sources and climate change mitigation*, ed. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. Von Stechow. Cambridge: Cambridge University Press.

Constantin, J., M. Willaume, C. Murgue, B. Lacroix, and O. Therond. 2015. The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well with limited data. *Agricultural and Forest Meteorology* 206: 55–68.

Coyle, W. 2007. The future of biofuels: A global perspective. *Amber Waves* 5: 24–29.

Craufurd, P.Q., and T.R. Wheeler. 2009. Climate change and the flowering time of annual crops. *Journal of Experimental Botany* 60: 2529–2539.

Daioglou, V., B. Wicke, A.P.C. Faaij, and D.P. Van Vuuren. 2015. Competing uses of biomass for energy and chemicals: implications for long-term global CO2 mitigation potential. *GCB Bioenergy* 7: 1321–1334.

Davies-Barnard, T., P.J. Valdes, J.S. Singarayer, and C.D. Jones. 2014. Climatic impacts of land-use change due to crop yield increases and a universal carbon tax from a scenario model. *Journal of Climate* 27(4): 1413–1424. doi:10.1175/JCLI-D-13-00154.1.

Dokoohaki, H., M. Gheysari, S.-F. Mousavi, S. Zand-Parsa, F.E. Miguez, S.V. Archontoulis, and G. Hoogenboom. 2016. Coupling and testing a new soil water module in DSSAT CERES-Maize model for maize production under semi-arid condition. *Agricultural Water Management* 163: 90–99.

Dornburg, V., and A.C. Faaij. 2005. Cost and Co2-emission reduction of biomass cascading: Methodological aspects and case study of SRF poplar. *Climatic Change* 71: 373–408.

Dornburg, V., B.G. Hermann, and M.K. Patel. 2008. Scenario projections for future market potentials of biobased bulk chemicals. *Environmental Science & Technology* 42: 2261–2267.

Dornburg, V., D. Van Vuuren, G. Van De Ven, H. Langeveld, M. Meeusen, M. Banse, M. Van Oorschot, J. Ros, G. Jan Van Den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lysen, and A. Faaij. 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science* 3: 258–267.

EPA. 2010. *Methane and nitrous oxide emissions from natural sources* . Washington, DC: U.S. Environmental Protection Agency.

FAOSTAT. 2015. *Food and Agriculture Organization of the United Nations Statistic Division*. Rome: FAO.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'hare, and D.M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311: 506–508.

Field, C.B., J.E. Campbell, and D.B. Lobell. 2008. Biomass energy: The scale of the potential resource. *Trends in Ecology & Evolution* 23: 65–72.

Frank, S., E. Schmid, P. Havlík, U.A. Schneider, H. Böttcher, J. Balkovič, and M. Obersteiner. 2015. The dynamic soil organic carbon mitigation potential of European cropland. *Global Environmental Change* 35: 269–278.

Gnansounou, E., J. Dong, and D. Bedniaguine. 2004. The strategic technology options for mitigating CO2 emissions in power sector: Assessment of Shanghai electricity-generating system. *Ecological Economics* 50: 117–133.

Harris, Z.M., R. Spake, and G. Taylor. 2015. Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy* 82: 27–39.

Hergoualc'h, K., and L.V. Verchot. 2014. Greenhouse gas emission factors for land use and land-use change in Southeast Asian peatlands. *Mitigation and Adaptation Strategies for Global Change* 19: 789–807.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences* 103: 11206–11210.

Houghton, R.A., J.I. House, J. Pongratz, G.R. Van Der Werf, R.S. Defries, M.C. Hansen, C. Le Quéré, and N. Ramankutty. 2012. Carbon emissions from land use and land-cover change. *Biogeosciences* 9: 5125–5142.

Hudiburg, T.W., S.C. Davis, W. Parton, and E.H. Delucia. 2015. Bioenergy crop greenhouse gas mitigation potential under a range of management practices. *GCB Bioenergy* 7: 366–374.

Hurkman, W.J., W.H. Vensel, C.K. Tanaka, L. Whitehand, and S.B. Altenbach. 2009. Effect of high temperature on albumin and globulin accumulation in the endosperm proteome of the developing wheat grain. *Journal of Cereal Science* 49: 12–23.

IEA. 2004. *Biofuels for transport: An international perspective*. Paris: International Energy Agency.

Ignaciuk, A. 2015. *Adapting agriculture to climate change*. France: OECD Publishing.

IPCC. 2007. *Climate change 2007: Mitigation of climate change. .Exit EPA disclaimer contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change,* ed. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer*.,* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. 2011. *Special report on renewable energy sources and climate change mitigation*. United Kingdom and New York: NY, USA, Cambridge University Press.

IPCC. 2013. *IPCC Climate change 2013: The Physical science Basis. Contribution of working group I to the Fifth assessment report of the Intergovernmental Panel on climate change,* ed. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Izaurralde, R.C., J.R. Williams, W.B. Mcgill, N.J. Rosenberg, and M.C.Q. Jakas. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecological Modelling* 192: 362–384.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. *European Journal of Agronomy* 18: 235–265.

Kalafatis, S.E., M.C. Lemos, Y.-J. Lo, and K.A. Frank. 2015. Increasing information usability for climate adaptation: The role of knowledge networks and communities of practice. *Global Environmental Change* 32: 30–39.

Kang, M.S., and S.S. Banga. 2013. Global agriculture and climate change. *Journal of Crop Improvement* 27: 667–692.

Kennedy, C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havránek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G.V. Mendez. 2009. Greenhouse gas emissions from global cities. *Environmental Science & Technology* 43: 7297–7302.

Kim, D.-G., D. Giltrap, and G. Hernandez-Ramirez. 2013. Background nitrous oxide emissions in agricultural and natural lands: A meta-analysis. *Plant and Soil* 373(1): 17–30. doi:10.1007/s11104-013-1762-5.

Kimball, B.A. 2011. Lessons from FACE: CO2 effects and interactions with water, nitrogen, and temperature. In *Handbook of climate change and agroecosystems: Impacts, adaptation, and mitigation*, ed. D. Hillel and C. Rosenzweig. London: Imperial College Press.

Knightes, C.D., and M. Cyterski. 2005. Evaluating predictive errors of a complex environmental model using a general linear model and least square means. *Ecological Modelling* 186: 366–374.

Lambin, E.F., and P. Meyfroidt. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108: 3465–3472.

Lobell, D.B., M. Banziger, C. Magorokosho, and B. Vivek. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change* 1: 42–45.

Loulou, R. 2008. ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. *Computational Management Science* 5: 41–66.

Macleod, M., et al. 2015. *Cost-effectiveness of greenhouse gas mitigation measures for agriculture*. Paris: OECD Publishing.

Mohammed, A.R., and L. Tarpley. 2009. High nighttime temperatures affect rice productivity through altered pollen germination and spikelet fertility. *Agricultural and Forest Meteorology* 149: 999–1008.

Morgan, J.A., R.F. Follett, L.H. Allen, S. Del Grosso, J.D. Derner, F. Dijkstra, A. Franzluebbers, R. Fry, K. Paustian, and M.M. Schoeneberger. 2010. Carbon sequestration in agricultural lands of the United States. *Journal of Soil and Water Conservation* 65: 6A–13A.

Nayak, D., E. Saetnan, K. Cheng, W. Wang, F. Koslowski, Y.-F. Cheng, W.Y. Zhu, J.-K. Wang, J.-X. Liu, D. Moran, X. Yan, L. Cardenas, J. Newbold, G. Pan, Y. Lu, and P. Smith. 2015. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agriculture, Ecosystems & Environment* 209: 108–124.

NRC. 2010. *Advancing the science of climate change*. Washington, DC: National Research Council. The National Academies Press.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, and K. Paustian. 2007. An empirically based approach for estimating uncertainty associated with modelling carbon sequestration in soils. *Ecological Modelling* 205: 453–463.

Ogle, S.M., F. Jay Breidt, M.D. Eve, and K. Paustian. 2003. Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997. *Global Change Biology* 9: 1521–1542.

Paltsev, S., J. Reilly, H. Jacoby, R. Eckaus, J. Mcfarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. *The MIT emissions prediction and policy analysis (EPPA) model: Version 4*, MIT joint program on the science and policy of global change. Cambridge, MA: MIT.

Paustian, K., N.H. Ravindranath, A. Amstel, and M. Gytarsky. 2006. Chapter 1 - Introduction. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme, ed. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe. Japan: IGES.

Pittock, B. 2003. *Climate change - An Australian guide to the science and potential impacts*, pp. 239. Report compiled for the Australian Greenhouse Office, Canberra, Australia. Available at http://www.greenhouse.gov.au/science/guide/index.html

Qin, Z., Q. Zhuang, and X. Cai. 2015. Bioenergy crop productivity and potential climate change mitigation from marginal lands in the United States: An ecosystem modeling perspective. *GCB Bioenergy* 7: 1211–1221.

Ravindranath, N., R. Manuvie, J. Fargione, J. Canadell, G. Berndes, J. Woods, H. Watson, and J. Sathaye (eds.). 2008. *Greenhouse gas implications of land use and land conversion to biofuel crops*. New York: Island Press.

Reddy, P.P. 2015. Agriculture as a source of GHGs. In *Climate resilient agriculture for ensuring food security*. India: Springer.

Rezaei, E.E., S. Siebert, and F. Ewert. 2015. Intensity of heat stress in winter wheat—phenology compensates for the adverse effect of global warming. *Environmental Research Letters* 10: 024012.

Roberts, K.G., B.A. Gloy, S. Joseph, N.R. Scott, and J. Lehmann. 2009. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science & Technology* 44: 827–833.

Ross, M. 2009. Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) model. Working Paper 09_01, April 2009,.RTI International, Research Triangle Park, NC.

Saadi, S., M. Todorovic, L. Tanasijevic, L.S. Pereira, C. Pizzigalli, and P. Lionello. 2015. Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. *Agricultural Water Management* 147: 103–115.

Sadras, V.O., V. Vadez, R. Purushothaman, L. Lake, and H. Marrou. 2015. Unscrambling confounded effects of sowing date trials to screen for crop adaptation to high temperature. *Field Crops Research* 177: 1–8.

Sala, O.E., F. Stuart Chapin III, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M.N. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. WALL. 2000. Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Sharma, S.K., and R. Chauhan. 2011. Climate change research initiative: Indian network for climate change assessment. *Current Science (Bangalore)* 101: 308–311.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32: 2099–2103.

Slade, R., A. Bauen, and R. Gross. 2014. Global bioenergy resources. *Nature Climate Change* 4: 99–105.

Smith, P. 2015. Addressing the joint challenges of climate change and food security. 5: 61.

Stöckle, C.O., M. Donatelli, and R. Nelson. 2003. CropSyst, A cropping systems simulation model. *European Journal of Agronomy* 18: 289–307.

Stratonovitch, P., and M.A. Semenov. 2015. Heat tolerance around flowering in wheat identified as a key trait for increased yield potential in Europe under climate change. *Journal of Experimental Botany* 66: 3599–3609.

Swaminathan, M.S., and P.C. Kesavan. 2012. Agricultural research in an era of climate change. *Agricultural Research* 1: 3–11.

Talukder, A.S.M.H.M., G.K. Mcdonald, and G.S. Gill. 2013. Effect of short-term heat stress prior to flowering and at early grain set on the utilization of water-soluble carbohydrate by wheat genotypes. *Field Crops Research* 147: 1–11.

Talukder, A.S.M.H.M., G.K. Mcdonald, and G.S. Gill. 2014. Effect of short-term heat stress prior to flowering and early grain set on the grain yield of wheat. *Field Crops Research* 160: 54–63.

Tao, F., Z. Zhang, S. Zhang, and R.P. Rötter. 2015. Heat stress impacts on wheat growth and yield were reduced in the Huang-Huai-Hai Plain of China in the past three decades. *European Journal of Agronomy* 71: 44–52.

Troy, T.J., C. Kipgen, and I. Pal. 2015. The impact of climate extremes and irrigation on US crop yields. *Environmental Research Letters* 10: 054013.

Turner, B.L., E.F. Lambin, and A. Reenberg. 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences* 104: 20666–20671.

Wang, B., D.L. Liu, S. Asseng, I. Macadam, and Q. Yu. 2015. Impact of climate change on wheat flowering time in eastern Australia. *Agricultural and Forest Meteorology* 209–210: 11–21.

Wang, X., J. Cai, D. Jiang, F. Liu, T. Dai, and W. Cao. 2011. Pre-anthesis high-temperature acclimation alleviates damage to the flag leaf caused by post-anthesis heat stress in wheat. *Journal of Plant Physiology* 168: 585–593.

Webster, M.D., M. Babiker, M. Mayer, J.M. Reilly, J. Harnisch, R. Hyman, M.C. Sarofim, and C. Wang. 2002. Uncertainty in emissions projections for climate models. *Atmospheric Environment* 36: 3659–3670.

Wei, D., N. Dormady, and A. Rose. 2015. Development of reduced-form models to evaluate macroeconomic impacts of greenhouse gas mitigation. *Journal of Sustainable Energy Engineering* 2: 377–397.

Williams, J.R. 1995. The EPIC model. In *Computer models of watershed hydrology*, ed. V.P. Singh. Colorado: Water Resources Publications.

Woli, P., B.V. Ortiz, D. Buntin, and K. Flanders. 2014. El Niño-Southern Oscillation (ENSO) effects on Hessian Fly (Diptera: Cecidomyiidae) infestation in the Southeastern United States. *Environmental Entomology* 43: 1641–1649.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1: 56.

Worldwatch. 2006. Worldwatch biofuels for transportation. Washington DC.

Wu, Z., H. Zhang, C. Krause, and N. Cobb. 2010. Climate change and human activities: a case study in Xinjiang, China. *Climatic Change* 99: 457–472.

Bao, Y., G. Hoogenboom, R. McClendon, and P. Urich. 2015. Soybean production in 2025 and 2050 in the southeastern USA based on the SimCLIM and the CSM-CROPGRO-Soybean models. *Climate Research* 63: 73–89.

Zhang, D., G. Pan, G. Wu, G.W. Kibue, L. Li, X. Zhang, J. Zheng, J. Zheng, K. Cheng, S. Joseph, and X. Liu. 2016. Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. *Chemosphere* 142: 106–113.

Zhang, H.-L., X. Zhao, X.-G. Yin, S.-L. Liu, J.-F. Xue, M. Wang, C. Pu, R. Lal, and F. Chen. 2015. Challenges and adaptations of farming to climate change in the North China Plain. *Climatic Change* 129: 213–224.