IMPLICATIONS OF LAND-USE PRACTICES ON NET BIOME PRODUCTIVITY AND CROP YIELD IN SOUTH ASIA

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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Environmental Science

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Dedication

Every challenging work needs self-efforts as well as the guidance of elders,

especially those who are very close to our hearts.

My humble effort, I dedicate to my sweet and lovely Father and Mother,

whose affection, love, encouragement and prayers of day and night made me successful in all my endeavours.

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Table of Contents

List of Abbreviations

CO_2	Carbon dioxide
Cflux	Carbon Flux
CFTs	Crop Functional types
CMIP5	Coupled Model Intercomparison Phase 5
DGVM	Dynamic Global Vegetation Model
GPP	Gross Primary Productivity
LUL	Land-Use Changes
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator
MPI-ESM-LR	Max Planck Institute Earth System Model Low Resolution
NEE	Net Ecosystem Exchange
NBP	Net Biome Productivity
NPP	Net Primary Productivity
PFTs	Plant Functional types
PNV	Potential Natural Vegetation
RCP	Representative Concentration Pathways
WHC	Water Holding Capacity

List of Tables

List of Figures

Abstract

Climatic Change impacts global weather patterns, agricultural yield and human life. These impacts of climate change are a result of increased greenhouse gas emissions from anthropogenic activities. The increase concentration of Carbon dioxide (CO_2), alters the carbon cycle and the carbon flux (Cflux). South Asia is very vulnerable to Climate Change and supports a huge population dependent on agriculture for their livelihood. The positive impacts of Climate Change include the increase in crop productivity due to fertilization effect caused by the increase in CO_2. However, the contribution of agricultural activities towards climate change is uncertain as a result of unmanaged grazing, tillage and harvest. The unmanaged land-use practices add to the land-use change. In this research the impacts of land-use change on the Net Biome Productivity (NBP) and Crop Yield were analyzed using the Dynamic Global Vegetation Models (DGVM); LPJ-GUESS for South Asia. DGVM's are used to study the shift that might occur in the vegetation patterns in the future as a result of land-use change. The spatial patterns and temporal trends for three time periods; Past (1851-1880), Present (1986-2012), and the Future (2071-2100) (RCP2.6 and RCP 8.5) were analyzed. The results revealed that in past there has been no effect on NBP due to absence of land-use changes. In present time, NBP has increased in some parts of South Asia, however, agricultural practices have also added to CO_2 emissions. In future under RCP8.5 scenario, high temperatures may result in further increased in CO_2 emissions. Modelled Cflux for South Asia associated with land-use change corresponded well with previous CO_2 estimates. Modelled average yields for the seven most important South Asian crops, were generally lower than reported FAO yields. Agricultural processes are key factors to be considered in the land– atmosphere Cflux for climate modelling.

Chapter 1

1. INTRODUCTION

1.1 Climate Change

Anthropogenic activities have resulted in 1ºC rise in the global average temperature above the pre-industrial levels. Another 0.8º C to 1.2º C change is expected between 2030 to 2052, if no actions are taken to reduce green-house gas emissions (IPCC, 2018). The global atmospheric carbon dioxide (CO_2) concentration was estimated to be 412.45 ± 0.1 ppm as compared to 280 ppm from the pre-industrial period (Friedlingstein et al, 2021). Global warming is defined as the increase in the global average temperature of the near surface wind as well as the ocean surface with a projection to increase further since the 20th century (Olaniyi. et al., 2019). The farming activities that mostly emit the greenhouse gasses are residue burning and the use of nitrogen fertilizers to increase the yield. Animal farming also releases a large amount of greenhouse gasses especially methane, ruminant animals i.e., sheep, cows, camels etc. release methane due to the unique design of their digestive system and the large animal farms that are kept to keep up with the meat and dairy demand of the ever-growing population and food industry release huge amounts of methane on annual bases and have a huge impact on global warming (Magomedov et al, 2021). The increasing projection of global warming with an increase in the global temperature above 1.5º C is a major cause of concert on how this change will impact not only the human life but also the food security for the increasing population (IPCC, 2018). The challenges in terms of land-use activities that we face now a days vastly vary across the globe, as a result of climate change these challenges will only get worse in the future while the socio-economic development could have both a positive or a negative impact on these challenges (IPCC, 2019). Land is one of the most important natural resources that provides human beings with the basis for their sustenance. Anthropogenic activities affect about 70% of the land (IPCC, 2019). Major changes in terms of crop production are required to continue sustainable production and to increase yield growth rate to keep up with the increasing demand (Pugh et al, 2016).

The storage of carbon by absorbing it from the atmosphere is known as carbon sink. Major carbon sinks are Ocean and Terrestrial (Nunes et al, 2020). The rate of exchange of carbon between various carbon sinks and the atmosphere is known as carbon flux. The changes that occur in the atmospheric carbon concentration are recorded annually as the carbon budget. The land-use changes that occur as a result of anthropogenic activities directly impact the terrestrial carbon flux by disturbing the balance of the terrestrial carbon pool. Climate Change and the carbon cycle are closely linked to each other. Changes in the carbon flux impacts the balance of carbon in the carbon cycle which in return has major impacts on the climate. Climate change is also responsible to disturb terrestrial carbon cycle by impacting different components of the carbon cycle and disturbing the balance of the carbon flux (Thompson et al, 2004). Studying the impacts of climate change on the terrestrial ecosystem is very important to evaluate how the climate change might affect terrestrial ecosystems especially the vegetation dynamics (Arora, 2019).

1.2 Green House Gas Emission and their Impacts

Greenhouse gas effect makes life possible on earth without it the average temperature of the earth's surface would be around -19^{o}C (Cassia et al, 2018). A problem arises with an increase in the greenhouse effect when the concentration of the greenhouse gasses increases the heat trapping capacity hence resulting in the increased greenhouse effect which is termed as global warming and is posing a threat to life on earth.

Greenhouse gas emissions have increased immensely in the last century due to industrial emissions; pre-industrial carbon dioxide emissions are calculated at 227 ppm in the year 1750 (Friedlingstein et al, 2020). The carbon dioxide emissions calculated for the year 2020 are 412.5 ppm, rise in emissions was 2.6 ppm over the year. Sources of Carbon emissions are increasing but the carbon sink is very uncertain in the future, due to uncertain land-use changes and land-use management activities.

Global warming and over population are major issues humanity is facing at the time, these threads need to be tackled for a sustainable and a prosperous future. Agriculture and Global warming both impact each other, agricultural activities play a major role in the emission of green-house gasses, which causes global warming and increase in global temperature has varying impacts on the agricultural activities i.e., carbon fertilization. The total emission from global livestock is 7.1 gigatons per year which makes up for 14.5 % of the total anthropogenic emissions (FAO, 2022).

Agricultural activities are responsible for 28% of the total anthropogenic emissions. The problem occurs when to meet the needs of the growing population agricultural activities are intensified, in return increasing the emissions of greenhouse gasses, the only solution to this problem is the sustainable agriculture (Magomedov et al, 2021). The impact of climate change on food production and agriculture is complex in a way that the food production is affected directly by changing in economic conditions hence impacting the agricultural demand.

Changes in land-use and land cover are associated directly to the changes in temperature and precipitation. Changes in temperature and precipitation are also associated with changes in yield production and greenhouse gas emissions. The atmospheric CO_2 concentration is supposed to increase by the end of century to 550-970 ppm (IPCC, 2020). The atmospheric CO_2 concentration is 413.2 ppm (WMO, 2020). Increased atmospheric carbon dioxide concentration is expected to have a positive effect on the crop yield due to carbon fertilization but the extent of carbon fertilization is unclear due to uncertainties in the management practices and varies in different crop types. With the atmospheric carbon dioxide concentration increased to 550 ppm the increase in the yield of C3 plants is 10-20% while for C4 plants it's only 0-10% with no possible improvement in the nutrient quality of the crops (Schmidhuber and Tubiello, 2007).

1.3 Agriculture and Climate Change

Agricultural sector is a major contributor to carbon emissions and is responsible for 24% of the total global emissions (IPCC, 2014). The contribution of agricultural sector to the global emissions is expected to increase as the food demand is increasing. The agricultural sector is not only responsible to keep up with the food demand but also provides a huge carbon sink (Lenka et al, 2015). Identification of emission sources in the agricultural sector is as important as the application of mitigation techniques. Agriculture is a contributor of greenhouse gas emissions but is also affected by climate change (Aydinalp & Cresser, 2008). The most important goal set in the mitigation practices in the agricultural sector is to increase the carbon storage capacity of soil. In order to achieve the goal of increasing carbon storage in the soil the measures that can be applied are increasing the water holding capacity (WHT) of the soil along with increasing the diversity of crop rotation, as well as including agricultural residue in the soil (Smith & Olessen, 2010). The major emissions from the agricultural sector include:

I. Carbon dioxide
II. Methane
III. Nitrous Oxide

The sources of agricultural emissions are dependent on the land-use management practices applied on crop management as well as soil management. The major sources of agricultural emissions are the agricultural machinery that is dependent on using fossil fuel to run, another source is tillage and decomposition of soil organic matter in high temperature (Pant, 2009). Rice paddies are one of the biggest sources of methane in the agricultural sector.

The sources of NO in the agricultural sector are the consumption of nitrogen-based fertilizers in order to increase the crop yield (Scialabba & Lindenlauf, 2010).

Climate change impacts the agricultural sector by directly impacting plant physiology and this impact can threaten the food security and requires mitigation techniques to reduce the impact of climate change on agricultural production (Mahato, 2014). It is expected that climate change will impact the agricultural sector both positively and negatively, but the negative impacts will have a higher effect. The negative impacts that are expected from the rising temperatures are increased evapo-transpiration which will reduce the soil water content. The reduced water content of the soil can be countered only if the precipitation levels increase as well (Cline, 2008). The predictions of declined precipitation levels will also impact the rain-fed agricultural model which is already practices by under privileged hence impacting their livelihood and survival.

The positive affect of climate change on agricultural sector is expected to be carbon fertilization as a result of increased atmospheric carbon dioxide concentration. The drawback that can come from carbon fertilization is reduced biomass as a result of lack of nutrients in the soil. With the changing climate the increasing temperature and the reduced precipitation will impact the water availability for agricultural sector (Karimi et al, 2018).

1.4 Land-use Change Practices and their Impacts

Many parts of the world are prone to land-use change (LUC) in the future. The anthropogenic LUC is impacting natural systems by changing the water resources, biodiversity along with the nutrient levels present in the soil (Ostberg et al, 2015). The LUC that the natural systems are facing currently are of two natures:

I. Directly as a result of anthropogenic involvement
II. Indirectly as a result of climate change

Climate change along with LUC determines the interaction between species and their environment in any given niche (Pacifici et al, 2017). Climate change is expected the species survival in the near future but at the current line LUC is the biggest threat towards any specie. LUC could be responsible for the loss about 8% the species in the terrestrial ecosystem (Powers and Jetz, 2019).

LUC are responsible for disturbing the carbon cycle by interrupting the interaction between terrestrial carbon sink and the atmosphere (Ramankutty et al, 2007). The various climatic factors including humidity, wind, temperature, etc., are also affected as a result of LUC by changing the bio-physical properties of the land surface hence creating heat island effects in urban systems (Paeth et al, 2009). The model dynamics that work on LUC are driven by anthropogenic activities but the incorporation of LUC in the climate model is very low making it harder to study the impacts of LUC, hence reducing the feasibility to apply the mitigation process to reduce the impacts of LUC on climate change (Liu et al, 2016). There are three types of LUC practices:

I. Managed Forests
II. Managed Grasslands
III. Croplands

Forest management includes specie selection along with harvesting, degradation and fire. The management of grasslands include, fertilization, grazing and mowing. As for the croplands they are managed tillage, fertilization, irrigation, irrigation and harvest (Pongratz et al, 2021). When it comes to modelling the LUC, spatial patterns of LUC are studied in the past and present in terms of social and economic conditions and the future predictions are made based on those conditions as well (Kozak et al, 2017). Factors Effect the Carbon Balance in the Terrestrial Ecosystem. The balance between carbon sink and sources is disturbed as a result of anthropogenic activities. Following factors affect the carbon balance in the terrestrial ecosystem:

1.4.1 Land-Use Changes (LUC)

The main LUC activities include in forest ecosystem are conversion to agricultural land, forest degradation, disease, fire, disturbances, conversion to agricultural land. The LUC in agricultural practices are tillage, harvest and fertilization they result in 24% of the global carbon emissions (Drummond and Loveland, 2010).

1.4.2 Carbon Fertilization

The increase in the atmospheric carbon dioxide concentration facilitates the photosynthesis process and increases the rate of photosynthesis (Wang et al, 2020). Respiration and the microbial decomposition process of vegetation counters the increased photosynthesis rate but the magnitude of the effect carbon fertilization will have on the carbon flux is uncertain (Behera et al, 2018).

1.4.3 Nitrogen Fertilization

The available nitrogen in the atmosphere is increasing due to human induced nitrogen in day-to-day activities especially in the agricultural sector. In agricultural sector nitrogen fertilizers are used to enhance the crop yield. The inclusion of N in agricultural sector disturbs the natural nitrogen cycle and the microbes responsible for the decomposition can't keep up hence increasing the atmospheric nitrogen concentration (Ouyang et al, 2018).

1.5 The Carbon Cycle

The exchange of carbon between the carbon sink and sources is known as the carbon cycle. The carbon cycle is a naturally balanced cycle that circulates the carbon between the atmosphere and the terrestrial and marine carbon sinks and sources (Figure 1.1). Carbon cycle is responsible for changes in the terrestrial and the marine ecosystem by directly exchanging the enhanced carbon concentration with the atmosphere. The increased atmospheric carbon concentration replenishes the carbon stores on land and ocean (Williams et al, 2019). The carbon taken up by the primary producers from the atmosphere is released back as a result of decomposition process and respiration. The carbon is stored in marine and terrestrial ecosystem in the form of fossils and sediments. The consumption of fossil fuel in various sectors of life is responsible to release that fossilized carbon back into the system, which disturbs the balance of the carbon cycle. The sedimentary carbon is released back into the atmosphere is result of direct or in direct anthropogenic activity. The direct activities that might be involved in the release of sedimentary carbon are disturbing carbon rich ecosystem to obtain minerals such as carbonates, limestone, etc., (Gordon, 2008). The most prominent anthropogenic impact that is involved in the release of sedimentary carbon is the release of carbon from ice sediments which have started to melt as a result of rising temperature (Hood et al, 2015).

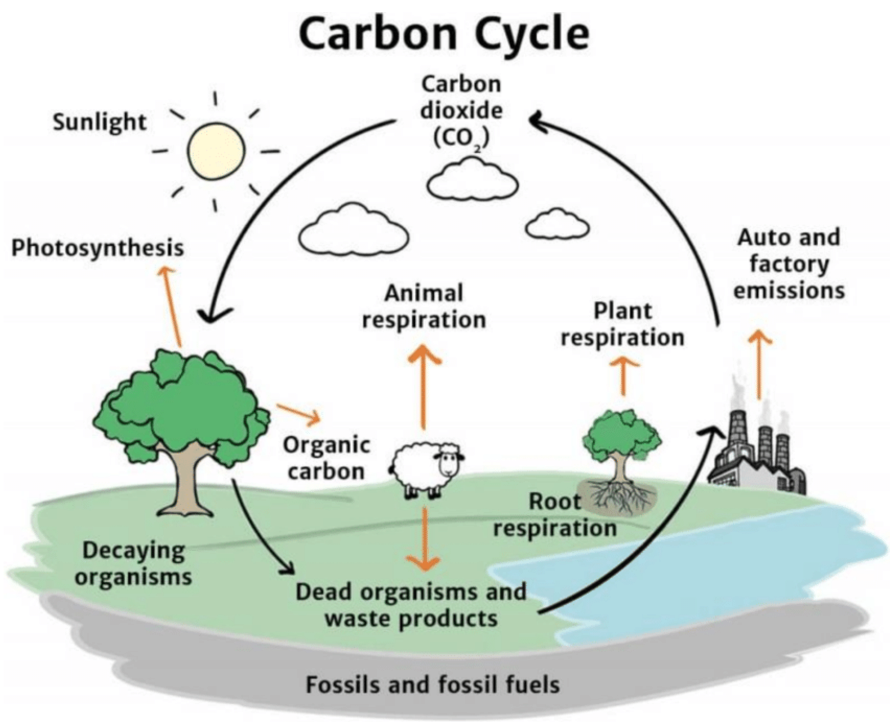


Figure 1.1: The Carbon Cycle

1.6 Terrestrial Carbon Flux

The feedback of the terrestrial ecosystem to the atmosphere is a result of atmospheric carbon concentration on the photosynthesis and the effect of climate change on the disturbances in vegetation, photosynthesis rate and respiration (Schimel et al, 2014). Land-use change also create large fluxes as a result of disturbance in the soil legacy flux hence reducing the carbon storage ability of soil. The positive variations in the terrestrial carbon flux can be the result of following factors:

I. Gross Primary Productivity (GPP).
II. Respiration
III. The loss in the carbon flux is a result of following factors:
IV. Land-use Changes (LUC)
V. Fire
VI. Disease
VII. Disturbances
VIII. Erosion
IX. Harvesting
X. Tillage

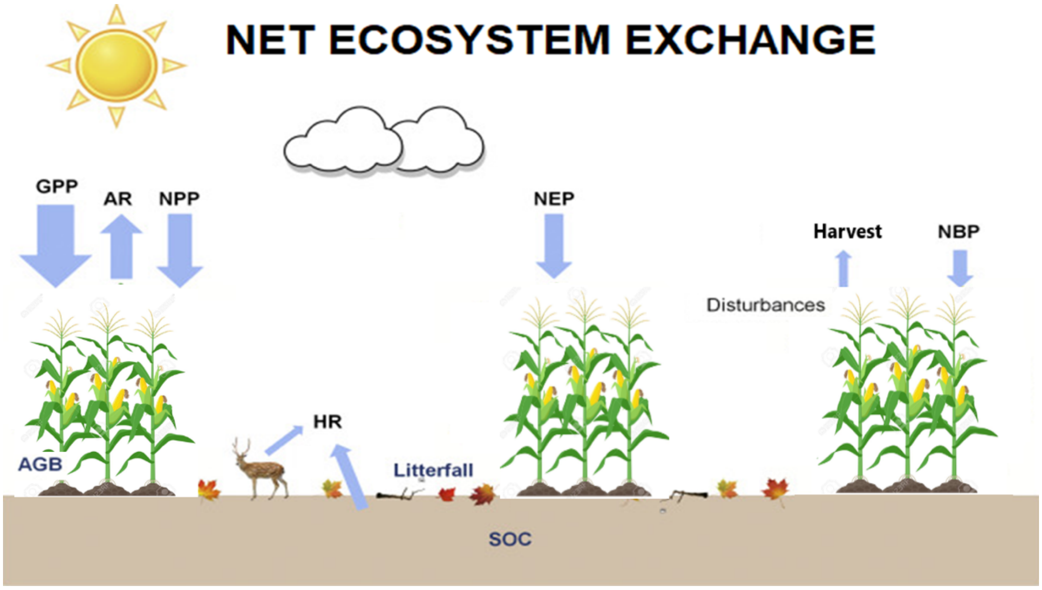


Figure 1.2: Net Ecosystem Exchange

The primary producers take up carbon as a result of photosynthesis process only a part of it is stored and the rest is respired back in to the atmosphere as autotrophic respiration (AR). The remaining stored carbon is the Net Primary Productivity (NPP) of that ecosystem (Figure 1.2). Losses from the NPP as a result of heterotrophic respiration (HR) and decomposition result in reducing the carbon stock even further the remaining carbon is the Net Ecosystem Exchange (NEE). Net Biome Productivity (NBP) is the remaining carbon stock after activities such as disturbances, fire or disease. The carbon fluxes in the terrestrial ecosystem can offset the emissions as a result of anthropogenic emissions by regulating the exchange between terrestrial ecosystem and the atmosphere (Beer et al, 2010).

1.7 Dynamic Global Vegetation Models (DGVM's)

The use of ecosystem models is increasing in order to assess the potential changes vegetation might experience and well as the changes in the carbon flux at regional scales as well as the global scale. DGVM's are a very important tool to study the terrestrial carbon cycle. The modelling features included in DGVM's are:

I. Biogeographical Processes
II. Biogeochemical Processes
III. Vegetation Dynamics

The processes included in DGVM's vary for each DGVM but the most common processes are:

I. Simulation of Daily Processes
II. Simulation of Annual Processes

Some models also simulate at leaf level by distributing the biomass in different parts of the vegetation. The model outputs are dependent on actual climate assumptions (Medlyn, et al, 2011). Some of the DGVM's developed by various research groups around the world are:

I. LPJ: Developed in Germany and Sweden
II. LPJ-GUESS: Developed in Sweden
III. IBIS: Developed in the United States
IV. MC1: Developed in the United States
V. HYBRID: Developed in the United Kingdom
VI. SDGVM: Developed in the United Kingdom
VII. SEIB-DGVM: Developed in Japan
VIII. TRIFFID: Developed in the United Kingdom
IX. VECODE: Developed in Germany
X. CLM-DGVM: Developed in the United States

Recent studies focus on studying the carbon flux, carbon pool and the LUC using DGVM's. A large gap is found in the carbon stock biomass allocation leading to biases in the future projections (Ahlstrom et al, 2012). Variation in DGVM's is accordance with how the plants are aggregated in each model, other features are inclusion of climate, mortality and biomass allocation.

1.8 Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS)

The DGVM used in this study is LPJ_GUESS developed by Ben Smith. (Smith et al, 2001). This model is used to simulate terrestrial ecosystem and landscape at regional and global levels. LPJ-GUESS is a process-based model and simulated daily and annual processes. LPJ-GUESS is used to study:

How the global vegetation is impacted by climate change (Sitch et al, 2003).

It can also predict the crop productivity in the future and the impacts of climate change on it.

I. LPJ-GUESS can simulate carbon flux and carbon pool.
II. 11 CFT's (Table1) have been defined to model using LPJ-GUESS.
III. LPJ-GUESS can differentiate between crop species depending on their characteristics

LPJ-GUESS can represent the photosynthesis process and the allocation of carbon as well as biomass in different parts of the plant. LPJ-GUESS works on both daily and annual processes, the daily inputs include; photosynthesis, radiation, temperature, precipitation, respiration, water balance and soil input. The input of the annual process include; plant growth, decomposition, mortality and establishment. The model outputs consist of tree density, leaf area index, types of vegetation, biomass, carbon fluxes and water fluxes (Figure 1.3).

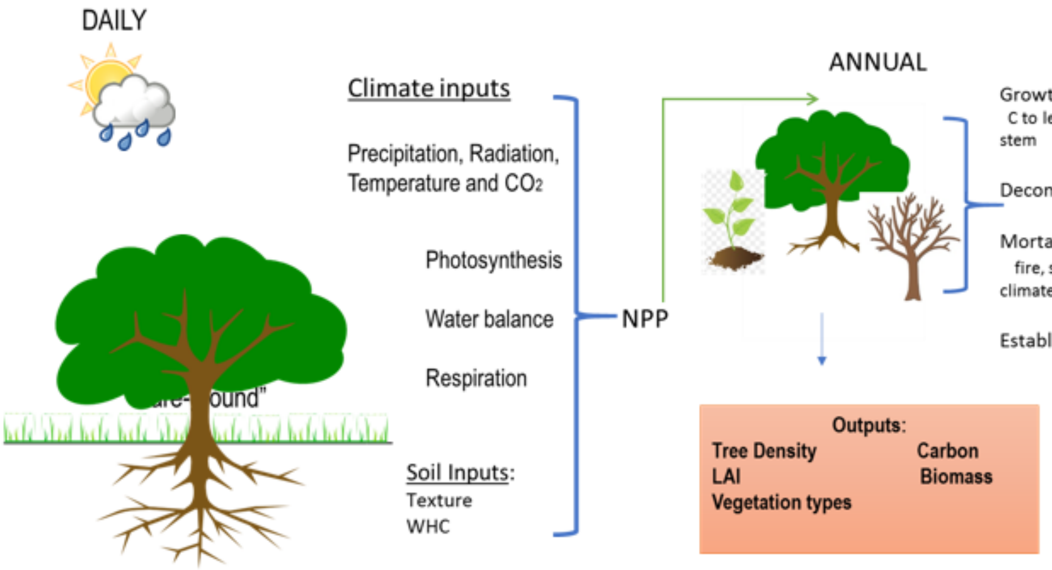


Figure 1.3: The Daily and Annual Processes included in LPJ-GUESS.

Chapter 2

2. LITERATURE REVIEW

2.1 Atmospheric Carbon Dioxide (CO_2)

Greenhouse effect is an important process to keep the temperature of the plant high enough to keep it habitable. In the last few centuries, the anthropogenic activities have been resulting in increasing the greenhouse gas emissions. The increase in the atmospheric concentration of the greenhouse gasses has resulted in increasing the global average mean temperature. The major activities that are responsible for the emission of greenhouse gasses are fossil fuel consumption and agricultural activities. The warming capacity of the Carbon dioxide (CO_2) molecule is lower as compared to other greenhouse gasses but increase in the CO_2 concentration in the atmosphere has been responsible for a major imbalance in the carbon budget (US EPA, 2016). The reason behind the warming effect of CO_2 is that it has a higher residence time in the atmosphere which is around 5 years. When compared to the pre-industrial conditions the greenhouse gas concentration has reached their peak levels in the past century (Ainsworth et al, 2020). A massive peak is observed in the atmospheric CO_2 concentration reaching almost 420 ppm as compared to less than 320 in 1960 (NOAA, 2021) (Figure2.1).

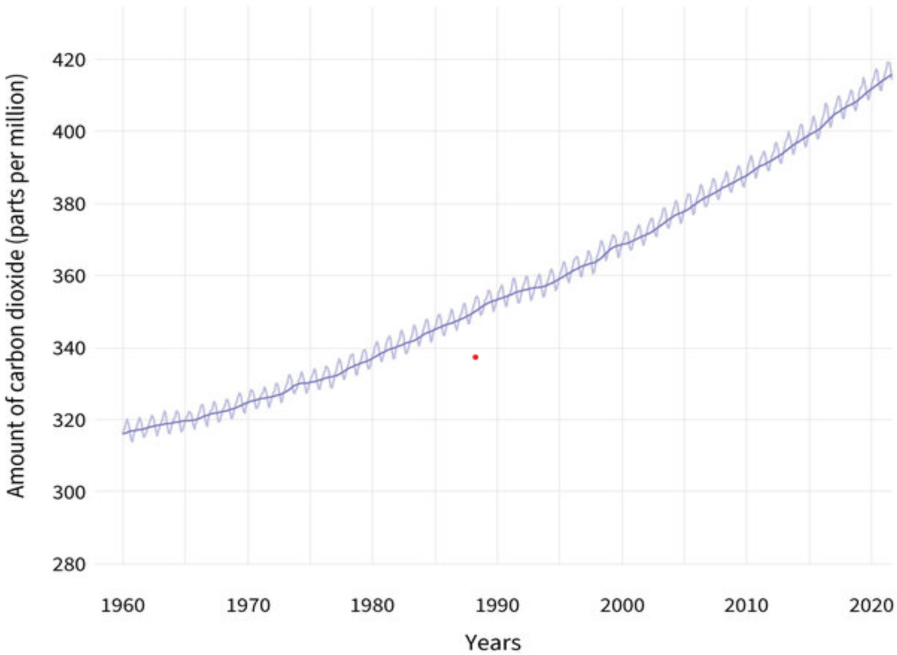


Figure 2.1: Atmospheric CO_2 Concentration (1960-2021) (NOAA, 2021).

2.2 Agriculture and Carbon Cycle

The relationship between the carbon cycle and agriculture in complex, they both have positive and negative impacts on each other. The conversion of forested land to managed land such as a grassland or a crop land not only accelerates the process of soil erosion but also the loss of soil carbon stock (Tang et al, 2019). The loss of the soil carbon stock is dependent on the climatic variables. The extreme weather patterns effect the terrestrial carbon cycle and disturb the feedback balance. The carbon allocation in the vegetation is one of the major uncertainties in terms of the terrestrial carbon cycle.

The increased atmospheric carbon concentration not only enhances the photosynthesis rate but also replenishes the terrestrial carbon sink, which in turn reduces the atmospheric carbon concentration and is replenished by exchange with terrestrial and marine carbon sink and the cycle goes on with both factors impacting each other in a feedback system.

Countries in South Asia have been going through economic reforms since the 1980's, most of the South Asian countries are agricultural focused and have been able to increase agricultural exports (Joshi et al, 2004). Agricultural sector in South Asia is responsible for providing people with livelihood and food security, but it is also one of the biggest contributors of greenhouse gas emissions (Kumara 2020). South Asia is vulnerable to Climate Change which will affect the livelihood of millions of people.

2.3 Land-Use Changes (LUC)

Agriculture has intense impacts on earth systems i.e., the global nutrient, water, carbon and the energy balance. Almost 50% of all vegetated parts of the land are impacted agricultural activities. (Bondeau et al, 2007) Management of land use and agriculture are the most important factor behind the terrestrial carbon cycle, as they impact the input rates of the organic matter through the processes of crop harvest, crop rotation, fertilization, residual decomposition, tillage and soil coverage. The organic matter input rates are also impacted by the agricultural management practices, by selecting the type of fertilizer and species. Organic matter flux of soil impacts the organic matter content in soil which determines the long-term soil fertility. It works like a feedback system between the carbon storage ability of soil, organic matter content and crop yield. (Oberholzer et al, 2014).

In the past the land use and land-cover changes played a dramatic part in changing the surface of the earth. It is expected that land use changes will continue in the future as a result of increased population, inclination towards more vegetable-based diet, changes in the crop productivity as well as the management practices in agriculture. In mitigation policies of climate change agricultural and land use management is a considerable option, but the approach has high uncertainty and the negative impacts that could be generated from these practices are unknown. For now, the terrestrial eco-system as a whole represents the carbon sink to be at net zero as well as a capacity to store anthropogenic carbon but only if it is managed properly. (Krause et al, 2016).

Land use and land cover changes (LUC) greatly impact the climate. The emissions from land use and land cover from the year 1750 to the present day are accountable for about the third of the overall anthropogenic emissions, and play a major part in the increase of global temperature to about 1°C above pre industrial era. Over the past few decades' land use practices and their impact on C fluxes and nutrient cycles has been a focus. In general, the soil erosion and decomposition process are accelerated due to agricultural activities because of the significant loss of carbon and absence of supplementary sources like nitrogen because of the primary deforestation process to clear the land for agricultural activities. (Krause et al, 2016). Net carbon flux from the land use and land cover changes is about 12% of anthropogenic carbon emissions between 1990-2010, this percentage is uncertain for many reasons including deforestation rate, forestation rate and the carbon density of the land that is undertaking the changes. The sinks and sources of terrestrial carbon stocks are very important for the global carbon budget. Over the period of 150 years the emissions from land use and land cover changes were estimated to be about 33%, 20% of them in just two decades (1980's and 1990's), 12% of these emissions between 2000-2009, the clear decline in the emissions is only because of increase in the fossil fuel emissions.

LUC Cflux doesn't represent the total Cflux because unmanaged land also contributes to the total Cflux. Terrestrial ecosystem is a net carbon sink presently, it's probably due to the LUC and the impacts of changes in the environment on growth of plants, such as fertilization, increased carbon and nitrogen concentration in the atmosphere as well as longer growing seasons due to rising global temperature, both managed and unmanaged lands are impacted by this hence contributing to the total net carbon flux. (Houghton et al, 2012).

Land-use changes are attributed to the changes in the bio-physical characteristics of the land as a result of anthropogenic activities. LUC is one of the major challenges on a global level with its contribution of impact the fluxed between carbon sinks and also impacts the biodiversity (Brihun et al, 2019).

2.4 Agriculture in South Asia

The increase in global population is increasing the food demand. Increasing agriculture yield in a sustainable method to fulfil the growing demand for food is the most important task in the sector to agriculture as well as food security. (Liu et al, 2020). Facing the increase in global food demand and limitation of land available for agriculture and labour, enhancing the productivity of agriculture is an essential solution for increasing agricultural yield to meet the increasing food demand, to solve the problem of malnourishment, reduce poverty and preserve the environment.

Crop models in South Asia show that by 2050 the crop productivity will decrease by almost 50% for different species of wheat as compared to 2000 levels, by about 17% for rice species and 6% for maize due to direct or indirect impacts of climate change. If climate change isn't considered in simulation scenario the population of malnourished children will decrease from 76 million to 52 million between the time period of 2000-2050 but considering the climate change the number will increase to 59 million in South Asia. (IFPRI, 2009). According to an experiment conducted on South Asia the agricultural trend is non-linear declining after reaching a certain point because of changes in variables that are agricultural land use changes, labour, use of fertilizer. (Liu et al, 2020)

When it comes to research in the field of agriculture focused on the developing parts of the world most of it is focused on sub-Saharan regions of Africa and China. South Asia doesn't get a lot of attention in terms of research on agricultural productivity. In some of the South Asian countries there had been a growth in agricultural productivity in the past due which started declining around 2002 due to unsustainable land use practices as well as unsustainable development practices. The major problem in the agriculture section in this region is the lack of social and environmental sustainability which can be solved with innovative incorporation of technology in agricultural sector. There has been obvious technical progress in the region but a decline in agricultural productivity, the obvious solution to this problem is sustainable agricultural practices. All of the South Asian countries: Bangladesh, India, Nepal, Pakistan, Sri Lanka experienced a slight improvement in the productivity due to technical improvements and weakened technology caused a decline in productivity in Bhutan. (Liu et al, 2020).

2.5 Agricultural Dynamics and LPJ-GUESS

CFT's capture extensive agricultural traits of plants and are generalized so they can be easily adapted for climate modeling. Besides the few alterations for yield producing parts CFT's are very well suited with the PFT's for the Potential Natural Vegetation (PNV). CFT's resemble specific clusters of crops that possess similar traits. To generalize the application of the model behavior of specific plant is not reproduced. To consider plasticity of variety dependent specific characters of crops are identified in local conditions. For CFT's carbon allocation-scheme on a daily base is used to capture the impacts of environment and management on yield production and development of crop. (Bondeau et al, 2007).

Terrestrial ecosystem can act as both the sink and the source for carbon emissions, according to estimations by the IPCC inter-governmental panel on Climate Change, It can hold about 2GtC/y. Vegetation as well as the soil play a part to uptake atmospheric carbon, which brings us to the new challenge faced by researchers when it comes to climate change mitigation is the land use management practices and how to conserve the carbon stocks and how to add to them. Documentation of the process has been mandated by IPCC.

Changes in land use practices cause a change in land cover and the carbon stocks associated to that land cover. The transfer of the change from one ecosystem to another can be a natural process but could also occur due to anthropogenic activities. The carbon carrying capacity of soil depends on the type of vegetation, precipitation received and temperature. If the carbon stock equilibrium is disturbed soil can act as either a source of sink for carbon, until a new balance is achieved. (Guo and Gifford, 2002).

2.6 DGVM Studies

Ma et al, (2022) investigated the symbiotic nitrogen fixation the legumes of grain using LPJ-GUESS. They simulated the carbon-nitrogen dynamics of vegetation for both LPJ-GUESS PFT's and CFT's. Plant growth parameters were simulated on daily basis according to the heat requirements of the developing plant. The net primary productivity and CO2 release was modelled as part of autotropic respiration. After the completion of development stage, the nitrogen consumption was reduced to 50%. The modelled data was compared with FAO data. Pearson correlation was used for the statistical analysis of the data. The study was concluded with results that the modelled data is very closed to observed data especially in site specific simulations, a linear relation was found between biological nitrogen fixation and legume yield. The relationship between nitrogen fertilizer rate and nitrogen fixation was found to be negative.

Ma et al, (2022) studied impacts of agricultural management on carbon stocks, nitrogen and crop productivity using LPJ-GUESS. They studied the impacts of seven different management practices on soil carbon pool, loss of nitrogen as well as the yield. Using LPJ-GUESS they simulated soil carbon stock and the productivity. Most of the simulations showed a decline in soil organic carbon (SOC) as a result of tillage and other management practices as compared to regions with conservative agricultural practices as observed in the field experiments. The regions with conservative practices show on average 11% increase in SOC and 22% increase in crop productivity as compared to managed agricultural practices. The study was concluded with the possibility of conservative agricultural practices as a solution for long term and more sustainable practices in terms of food security especially in poor soil conditions.

Emmet et al, (2021) evaluated the LPJ-GUESS-LMfireCF's ability to model fire, regional biomass and biogeography of the plants. LPJ-GUESS provides the forest demography in cohort mode while the LMfire provides a fire module with an extension of CF that provides crown fires and stand replacement. The model calculates the crown and fire characteristics and then simulates if the fire initiation and spread characteristics are present and to what extent. The model performance was evaluated by comparing the historical simulations from LPJ-GUESS-LMfireCF with the historical simulations from GlobFIRM. The simulations from LPJ-GUESS-LMfireCF were overestimated by 12% when compared with the satellite data but it simulates the plant regrowth after fire events to be faster than field-based experiments. The simulations from GlobFIRM overestimated the simulations by five percent in comparison to the satellite data.

Pongracz et al, (2021) studied biogeochemistry of arctic and sensitivity of the perma-frost using LPJ-GUESS. A multi-layer snow scheme was used instead of single layer snow scheme for this study which reduced the overestimation of declining perma-frost by 5-10%. The dynamics of the perma-frost were simulated using the characteristics of the soil layers that were 15 in number. They thermodynamics of the soil layers were determined by presence of snow and the climatic conditions. The thermodynamic properties were dependent on organic contents of the soil, water, ice, mineral and air. The results of the study deduced that the new multi-level snow scheme better reproduces the cold weather as compared to static scheme as a result of consistent snow density throughout. Carbon pool and productivity were also analyzed and the results showed that the carbon pool is low across the region. The reason behind low carbon pool is that the pool is represented by only the top layer that is 50cm in depth.

Herzfeld et al, (2021) investigated the dynamics of organic content of soil from agricultural management practices using LPJml. Using the model, they analyzed the historical evolution of the soil organic carbon (SOC) which revealed the global SOC stock to be around

2650 Pg C stored in the cropland soil. The development in the SOC of the future simulations were projected under the ideal and the extreme climate scenario and suggest a declining SOC stock in both scenarios, as a result of increased decomposition in SOC from managed agricultural cropland. The tillage practices influence the future SOC stock by the extent of about 0.2-1.3% while the residue management plays a vital role. They also found that the decline in the SOC is declining by 1-1.4% only by the end of the century unless the residue is harvest. In case of residue harvest the decline is around 26-27%.

Oberpriller et al, (2021) studied sensitivity of climate parameters and uncertainties in the projections of climate stock. They used LPJ-GUESS to analyze sensitivity in the vegetation dynamics considering modelling parameters as well as climatic drivers. They found that the projections of the forest are mostly driven by water retention ability of soil, photosynthesis rate and mortality, while the future predictions are mostly influenced by the climatic drivers. They suggested that the uncertainty in the predictions increases with the increase in temperature and that the climatic variables dominate at the extreme end of the gradient. They also suggested that the climate variables not only influence the model prediction but also modifies sensitivity and uncertainties in an ecosystem.

Lindeskog et al, (2021) studies forest management for the estimation of forest carbon stocks using LPJ-GUESS. Multiple age groups, specie structures and harvest techniques are introduced. Different agricultural management techniques are applied and are evaluated against the harvest data and the standing stem volume. Modelled carbon stocks are compared with the reported carbon stocks data, the increase in the simulated carbon stock is by 32% for years 1991-2015. The simulated carbon stock, sink and growth is very close to the reported values for the year 2010. The density of the carbon sink for year 2000-2007 equates 63% of the reported data indicating uncertainties in the soil carbon flux. The net annual increment values are very close to the reported values.

Usman et al, (2021) investigated the primary productivity of Himalayan Hindu Kush (HKH) Forest under climate change using LPJ-GUESS. The model projections of vegetation carbon, terrestrial productivity and Net Biome Productivity (NBP) were driven by 3 CMIP5 models. The projections were compared with observed data. From this study they deduced that the modelled NBP is reducing for years 1986-2015 as a result of land-use changes. For the future projections the NBP is increasing under both ideal and extreme scenarios. It was reported that the HKH region will be an active carbon sink under both climate scenarios. As for the vegetation carbon the extreme projections show higher carbon stock which is mostly attributed to carbon dioxide fertilization effect.

Forest et al, (2020) induced vegetation dynamics in the general circulation model enabled by atmospheric chemistry by developing a link between LPJ-GUESS and EMAC. They coupled LPJ-GUESS with EMAC, the framework of LPJ-GUESS is eco-physiological and includes photosynthesis. Respiration, carbon, nitrogen and water cycle and includes a comprehensive representation of resources, plant growth, disturbances such as fire, and vegetation dynamics. The EMAC and LPJ-GUESS were evaluated with one way coupling at multiple spatial resolutions and were compared with the map of Potential Natural Vegetation (PNV) that included tree cover, canopy height, biomass and gross primary productivity, there are some discrepancies in the PNV simulations. Normalized mean error was used to quantify the gridded dataset. The lower resolution datasets show increment by 10% while the higher resolution by further 4%. These results show results just 4% worst by LPJ-GUESS simulations. When GPP is removed the results get worse by 10%.

Pugh et al (2015) simulated the carbon emissions as a result of land-use changes and the impact of agricultural management. They accessed the impact of land-use management in vegetation dynamics in crop management. When the management practices such as tillage, harvest and grazing were incorporated in to the simulations the resulted land-use change emissions were 80% larger than when these practices are ignored. When the timescale of the emissions is changes the over estimation of the carbon emissions occurred due to reforestation practices. They reported that the management practices have a huge impact on food security but have a very little influence in land-use change emissions.

Lindeskog et al, (2013) investigated the implications of land-use change in ecosystem carbon cycle using LPJ-GUESS. They integrated crop and pasture lands and management of natural vegetation its recovery after the crop land is abandoned in to the model. They applied the model to study impact of land-use change on net carbon balance of an ecosystem and tested the model’s ability to simulate crop productivity. They reported that the regions that have large managed crop lands the FPAR vs NDVI fit is improved significantly. They also modelled the most important crops of their study are and compared then with the available data from FAO, the modelled yield was reported to be higher with the yield gap factor of about 2-6.

2.7 Significance of the study

South Asia is characterized by a faster than global average population and is increasing its food and energy production for the growing population by expanding agricultural land and burning more fossil fuels. A carbon budget, the net gain or loss of carbon, for this region will enable the constraining of other neighboring regional fluxes and act as an overall constraint on the global carbon budget. The region has a history of intensive land-use change (LUC) activity such as intensive cultivation and overgrazing of pasturelands and transitioning forestland to agricultural land. A great deal of concern has been raised regarding to what extent such rapid changes in LUC and management practices have affected the carbon stock, thereby impacting the net land-atmosphere carbon flux, which is essential for ecosystem sustainability.

2.8 Research Objectives

The objectives of the study were:

- To assess total Net Biome Productivity (NBP) under Land-use Changes using past and Future Climate Scenarios in South Asia.
- To assess total crop yield under two climate change scenarios and comparison with observed yield data for South Asia

Chapter 3

3. METHODOLOGY

3.1 Study Area

South Asia is bounded by Himalayas and the Indian ocean and is located at 25.0376° N and 76.4563° E (Figure 3.1). The countries included in South Asia are Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka. South Asia is host to 24% of the world population (Worldometer, 2021). The most common crops of the region are Wheat, Rice, Maize and Soybean. Rice covers the most agricultural land in the region with Pakistan and India as two of the world's largest exporters of rice. 57% of the land cover in South Asia is agricultural land and about 60% of the population engages in agricultural activities. Although South Asia is one of the largest producers of agricultural products but is the hungriest region in the world, the Global Hunger Index score of South Asia is 30.5. (Asian Farmers' Association for Sustainable Rural Development (AFA), 2019).

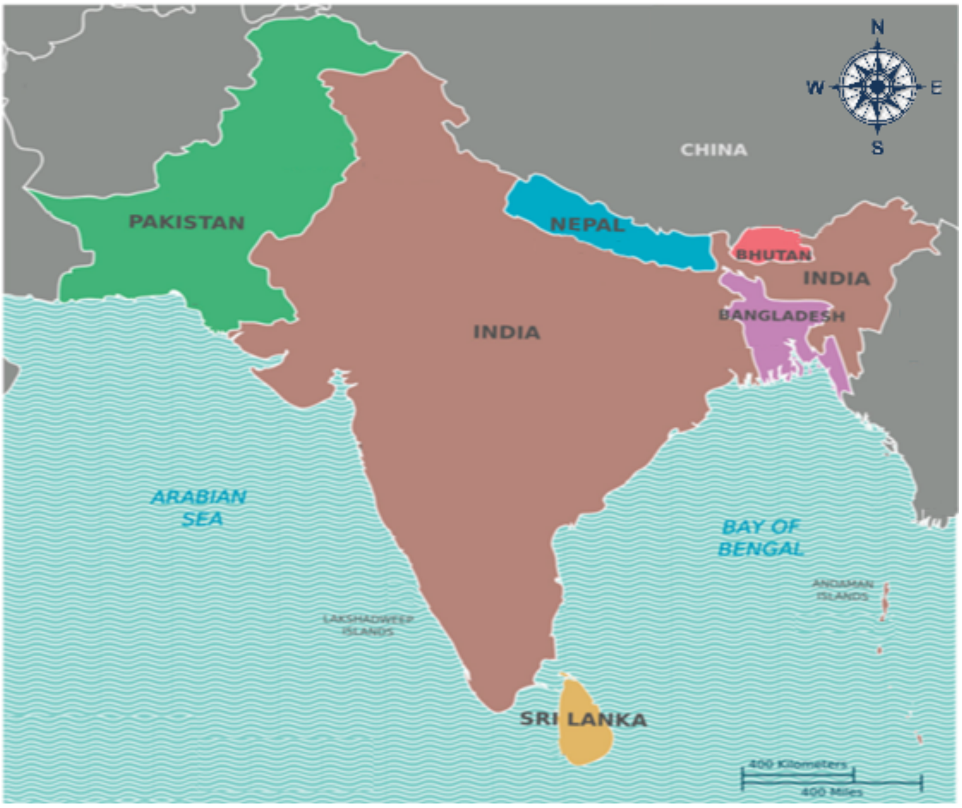


Figure 3.1: South Asia one of the most population dense regions of the World, encompassing Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka.

The methodology followed to carry out this study is illustrated in Figure 3.2.

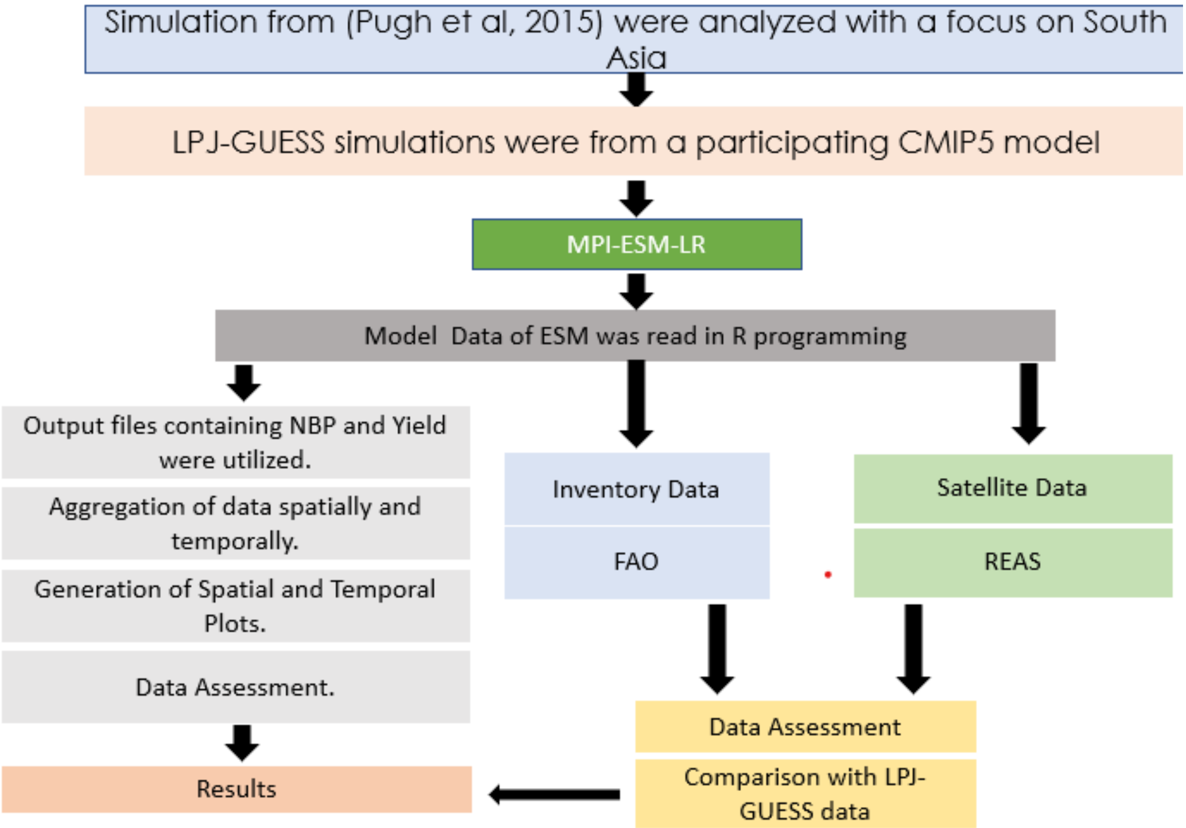


Figure 3.2: Methodology Flowchart

3.2 LPJ-GUESS Settings

Climate Simulations from Pugh et al. (2015) were reanalyzed for this study with focus on South Asia as a selected study area of the research. Spatial patterns and temporal trends of Carbon flux with the focus on Net Biome Productivity (NBP) were investigated along with spatial patterns and temporal trends in yield production and Land-use Land cover change in the study area. The output resolution of LPJ-GUESS was set at 0.5^{o} X 0.5^{o}. The climate model used for the study is a CMIP5 climate model i.e., MPI-ESM-LR or Max Plank Institute Earth system Model, Low Resolution. The historical data for the model was obtained from CRU TS 3.21 (CRU, 2013) Global Climate for the time period 1850-2012. The future model projection outputs were extracted under RCP 2.6 and RCP 8.5. RCP or representative concentration pathways is a concept first presented in the IPCC fifth assessment report (IPCC, 2014). RCP 2.6 is considered an ideal scenario in which the emissions as a result of fossil fuel consumption has been reduced due to shift towards alternative energy resources and from applications of carbon capture techniques. RCP 8.5 is considered an extreme scenario in which minimum efforts are put in to reduce carbon emissions and the primary energy sources are fossil fuels

(Engstrom et al, 2016). The dynamic vegetation response as a result of climate change is represented using Crop Functional Types of CFT's (Table 3.1) in LPJ-GUESS.

Table 3.1: The Crop Functional Types of LPJ-GUESS (Pugh et al, 2015).

Crop Functional Type	Model Output Code	Types of Crops
Temperate Cereals	Teww	Wheat, Barley and Rye
Tropical Rice	TrRi	Rice
Temperate Maize	TeCo	Maize
Tropical Cereals	TrMi	Millet and Sorghum
Temperate Pulses	TePu	Pulses
Temperate Roots	TeSb	Potatoes and Sugar beet
Tropical Roots	TrMa	Cassava
Temperate Sunflower	TeSf	Sunflower
Temperate Soybean	TeSo	Soybean
Tropical Groundnuts	TrPe	Peanuts
Temperate Rapeseed	TeRa	Canola

3.3 Model Output

Table 3.2: List of Model Output.

Abbreviation	Full Name	Brief Description
Cflux	Carbon Flux	The amount of carbon exchanged between carbon pools and the atmosphere.
NBP	Net Biome Productivity	The amount of carbon stored in the sink after the removal of non-respiratory losses.
LUC	Land-use Changes	The changes in bio-physical characteristics of the land as a result of anthropogenic activities.
Yield	Crop Yield of different CFT's	The amount of agricultural product harvested per unit area.
PNV	Potential Natural Vegetation	Vegetation without any LUC

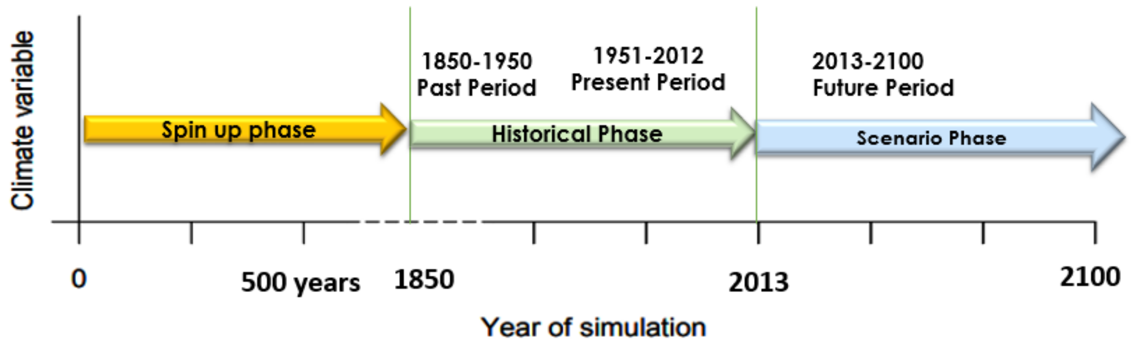
3.4 Data Analysis

The data acquired from Pugh et al. (2015) was analyzed using R- programming Software RStudio (Allaire, 2009). The shapefile for South Asia was acquired from Data Basin (Data Basin, 2022). In order to analyze the model output of LPJ-GUESS an R-package DGVMTools (Forest et al, 2019). DGVMTools has the ability to analyze the model output spatially and temporally. Using DGVMTools that data was split into timelines in order to study the changes in spatial and temporal patterns overtime and then plotted according to the requirement of the study objectives. Various R-packages including Raster, ggplot2, sp and rgeos etc. were used to analyze the raw data and produce high resolution results.

3.5 Data Timeline

Model Simulations were split into 3 time periods (Figure 3.3) by following the below timeline:

I. The past period (1851-1880).
II. The present period (1986-2012).
III. The Future period (2071-2100).



<u>**Not drawn to scale**</u>

Figure 3.3: Time Scale Division.

3.6 Calculation of Carbon Intensity

The Carbon Intensity is the difference between the modelled accumulated carbon emissions and the accumulated land-use change. Carbon intensity provides us with the data of legacy flux to compare and understand the impacts of historical changes in the land-use and carbon emissions, the drivers of those emissions and land-use changes and how those drivers impact the land-use change the Cflux in the present and future periods.

3.7 Difference between Transient Land-use and Fixed Land-use

In the model output for historical simulations there are two types of land-use scenarios:

I. Fixed Land-use

II. Transient Land-use

3.7.1 Fixed Land-use

In fixed land-use scenario the land-use is fixed at 1850 with the carbon dioxide emission level fixed at 1850 level which was estimated to be around 289 ppmv (Pugh et al, 2015). Fixed land-use scenario provides us with an overview of the land-use scenario with exploitative changes in the bio-physical characteristics of the land and without increase in the carbon emissions since the year 1850. Using this scenario, we estimate changes in the Net Biome Productivity and yield patterns without any extensive land-use changes.

3.7.2 Transient Land-use

In transient land-use scenario that land-use is changing after a short period of time and the carbon dioxide emission level was fixed at 1985 level which were 330 ppmv (Pugh et al, 2015). The transient land-use scenario provides the projection of changing land-use and increasing emission levels as a result of anthropogenic activities and their impact on both Net Biome Productivity and the yield in the region.

3.8 Trends in Net Biome Productivity

Mann Kendall test is used to analyze the Net Biome Productivity (NBP) trend in South Asia for years 1961-2012. The raster for each year is stacked and the cropped and masked using the shapefile of South Asia. Using the R-package MKraster the Mann Kendall test is run on the raster stack after which it is plotted using basic R-packages to produce quality results.

3.9 Correlation between Modelled Land-use Changes and Observed Carbon Emissions

The Land-use changes calculated using the simulated model output was correlated with the observed Carbon dioxide emission data acquired from Regional Emission Inventory in Asia (REAS) (REAS, 2021). Mann Kendall test was applied using R-package MKraster along with rastervis and gridextra to correlate the modelled data with observed data for years 1961-2012. The correlated data was then plotted using basic R-packages to produce high quality results.

The land-use change modelled data was acquired by subtracting the transient land-use data from the fixed land-use data for historical simulation period from the CRU historical data. In order to correlate the two data sets the raster for each year from both data sets were stacked and resampled before Mann Kendall test is run using R-package MKraster. After the test the new raster sets are cropped and masked using the shapefile of South Asia before plotting the final results by applying threshold value of >=0.05 for p-value.

3.10 Trends in Yield

In order to analyze yield trends in South Asia Mann Kendal test was used. The raster sets for years 1961-2012 were stacked and then analyzed using R-package MKraster in order to analyze the trend in yield. The trend results are plotted using basic R-packages to represent them in high resolution.

3.11 Comparison between Modelled and Observed Yield

The modelled yield was compared with observed yield data obtained from Food and Agricultural Organization (FAO) (FAO, 2021). Both data sets were organized in Excel for years 1961-2012. The organized data set was analyzed and plotted using basic R-packages. Data was compared using identity line or 1 to 1 line with Observed data at the x-axis and modelled data plotted at the y- axis of the graph. The identity line between modelled and observed data is analyzed to calculate the yield gap between both data sets in order to determine the accuracy of modelled yield data for South Asia.

Chapter 4

4. RESULTS AND DISCUSSIONS

For this research, the output from the simulations were split into different timelines: past period (1851-1880) and present period (1986-2012) under two land-use scenarios:

I. Transient Land-use

II. Fixed Land-use

For the future period (2071-2100) the projections are under two Representative Concentration Pathways (RCPs):

I. RCP 2.6: The ideal Scenario

II. RCP 8.5: The Extreme Scenario

The results are discussed below.

4.1 Carbon Intensity

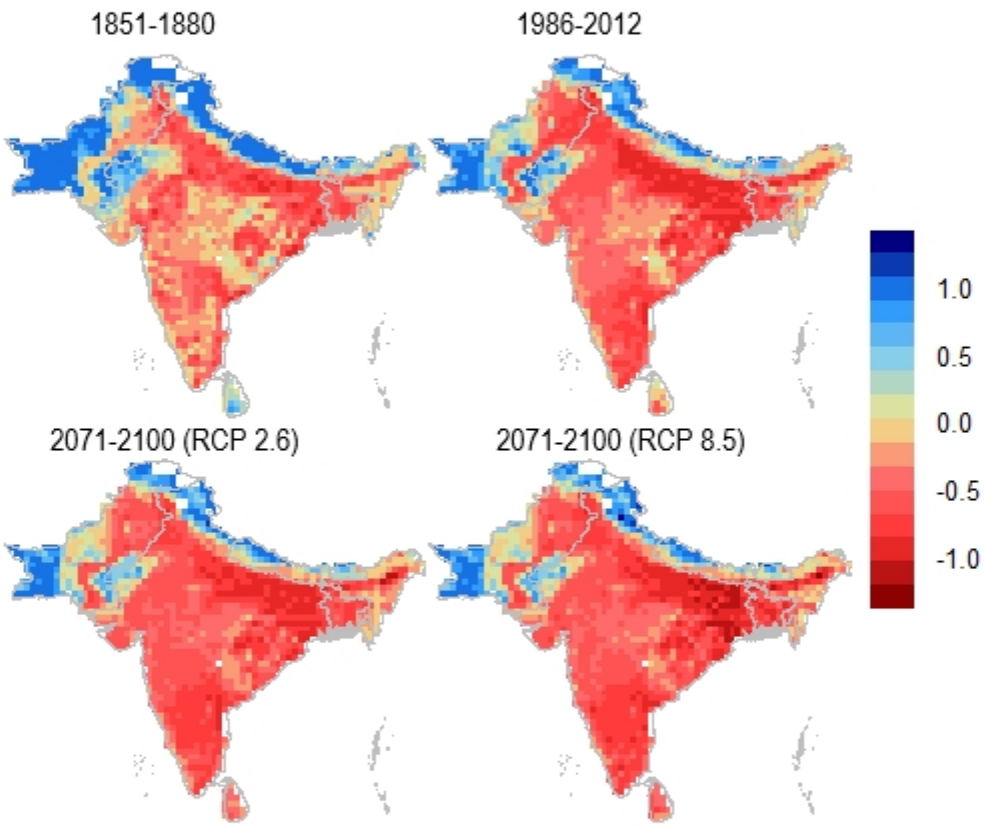


Figure 4.1: Carbon Intensity indicating Land-use change Fractions.

The Carbon Intensity of South Asia is increasing when compared between Past, Present and the Future periods (Figure 4.1). The increasing carbon intensity is consistent in regions with increasing land-use change in the present and future periods as well. The increasing carbon intensity could be an indicator of intensity carbon uptake as a result of agricultural practices and hence the Land-use change. The changes in Carbon Intensity of the region are mainly due to interactions between climate drivers at regional levels. The historical changes in carbon intensity are responsible for driving the ecosystem carbon cycle long after those changes might have occurred (Krause et al, 2020). Historically the Carbon Intensity is impacted by land-use change and harvest activities.

4.2 Land-use Change in South Asia

In order to calculate LUC, the difference between NBP under RCP's and PNV's were calculated.

For each scenario the timeline was split into Past (1851-1880), Present (1986-2012), and Future (2071-2100) periods. Each period was spatially analyzed under both scenarios and for LUC under RCP 2.6 the difference between RCP and PNV 2.6 was calculated and for LUC under RCP 8.5 the difference between RCP and PNV 8.5 was calculated in order to get the idea of LUC in all past and present and to make prediction for the future trends in LUC. The positive values indicate carbon sink while the negative values indicate carbon source.

4.2.1 Land-use Changes under RCP 2.6

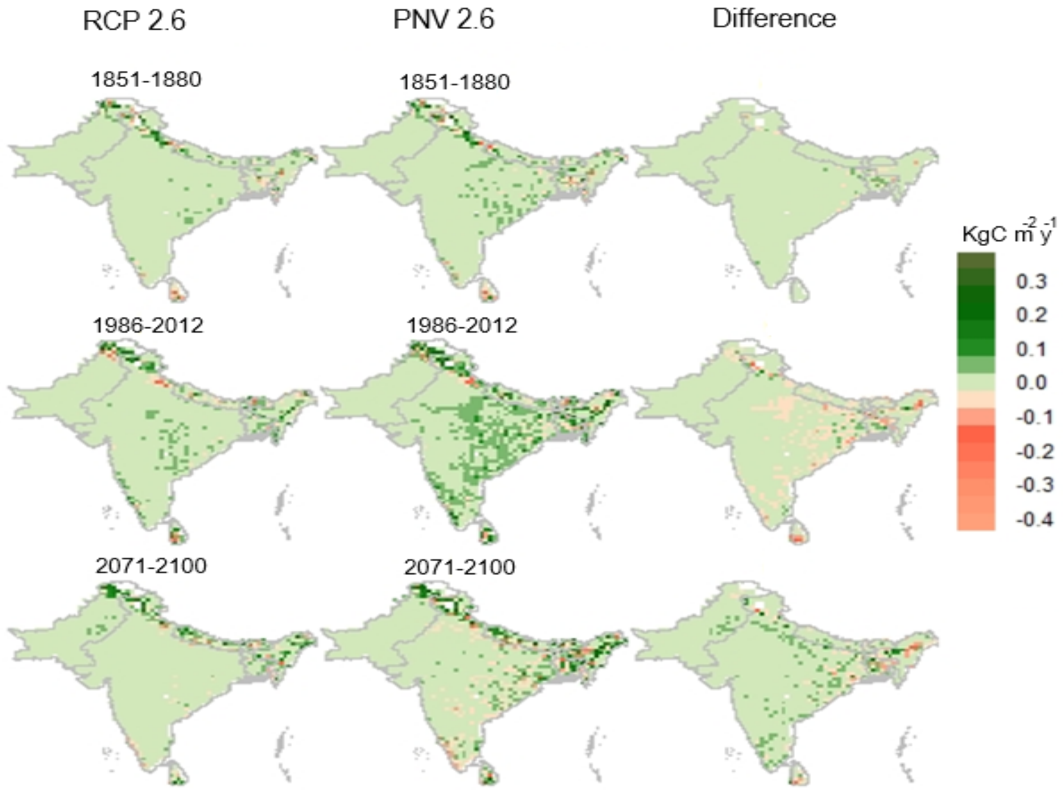


Figure 4.2: Spatial Patterns in Land-use Changes under RCP 2.6 for Past, Present and Future periods.

During the past period the LUC is very low and the small amount of LUC is indicated in northeast India and Bangladesh (Figure 4.2). In the present the LUC activities have increased intensively as compared to the past with more area acting as a source of carbon emission and some area acting as carbon sink. For the future, the LUC have increase with an increase in the carbon sink as compared to the past. The reason behind an increase in the carbon sink is an indicator of reduced emissions and application of carbon capture techniques as RCP 2.6 is the lowest concentration pathway.

Land-use Changes under RCP 8.5

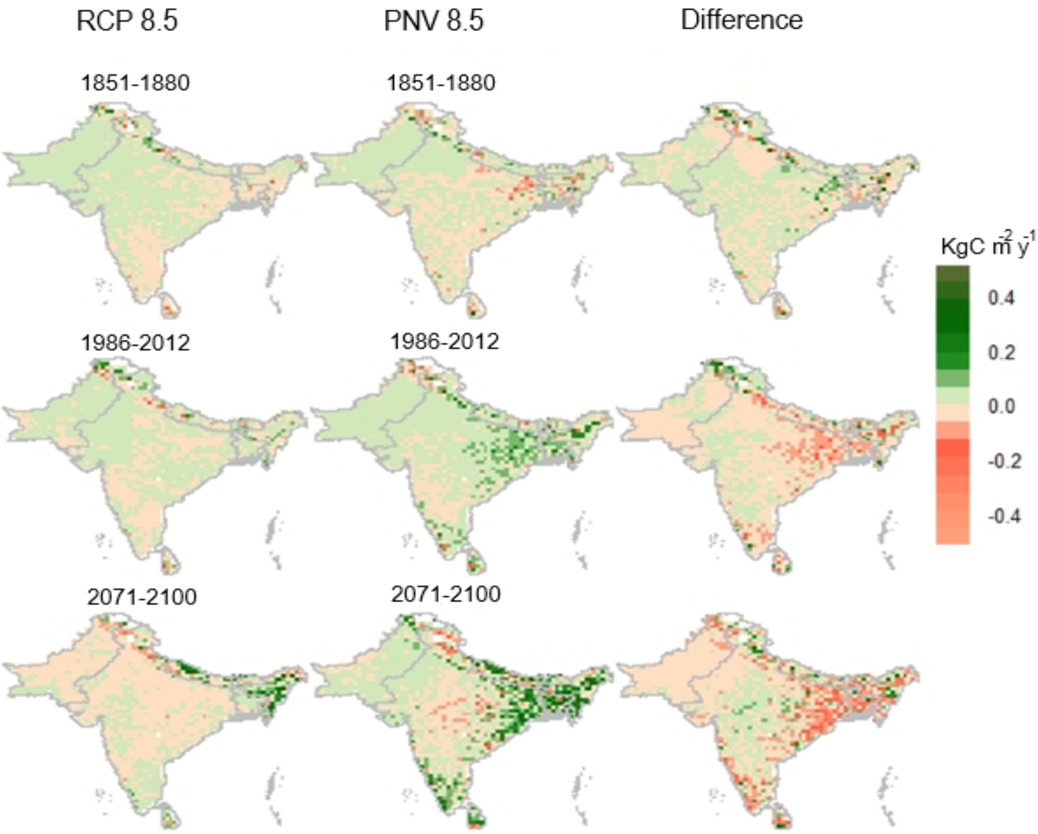


Figure 4.3: Spatial Patterns in Land-use Change under RCP 8.5 for Past, Present and Future periods

For the past period the LUC under RCP 8.5 is very high with almost the whole region as a carbon sink with few indicators of carbon sources mostly indicated in the north of the region. The LUC in the present are increasing as compared to the past with carbon sources increasing intensively over time (Figure 4.3). The Khyber Pakhtunkhwa province in Pakistan is acting as a carbon sink while the rest of South Asia is a huge source of carbon emissions. The hotspots of carbon emissions are near the coast line in India near the Bay of Bengal (Figure 4.3). In the future, the LUCs are getting more intensive with a drastic increase in the carbon emission sources, the carbon sinks under RCP 8.5 are also increasing with some positive points spread across the map (Figure 4.3). The reason behind an intensive increase in carbon emission sources under RCP 8.5 is a result of use of fossil fuel emissions as a result of anthropogenic consumption and almost no alternatives applied to reduce carbon emissions.

The carbon sinks in the future are a result of carbon fertilization effect as a result of increased atmospheric carbon concentration. Another thing to note here is that in order for vegetation to have a healthy growth is the presence of proper nutrients without the presence of nutrients the vegetation growth starts declining (Soares et al, 2019). For the future simulation the nutrient levels, disturbances and disease was not considered in these projections.

4.3 Net Biome Productivity of South Asia

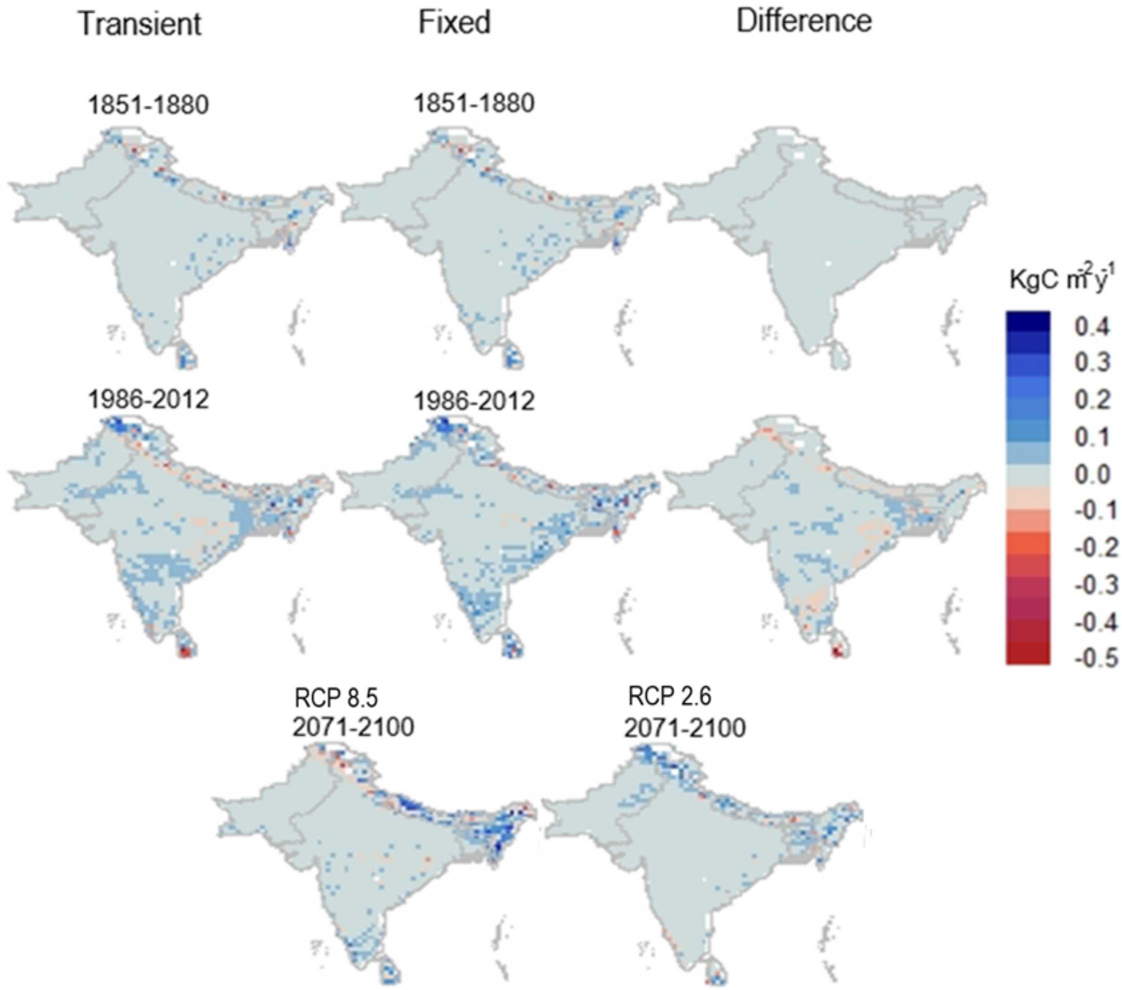


Figure 4.4: Spatial Patterns in the Net Biome Productivity of South Asia in Past, Present and Future period.

In order to analyze the Net Biome Productivity of South Asia the timeline was split into Past (1851-1880) and present (1986-2012) under transient and fixed land-use and the future (2071-2100) under RCP 8.5 and RCP 2.6. For each time period the differences are calculated between transient and fixed land-use scenarios for past period and the present period to calculate land-use changes in that respective period.

The positive values in figure 4.3 represent the carbon sinks on the region while the negative values indicate the sources of carbon emissions. In the past period under both transient and fixed land-use most of the NBP is neutral and is neither acting as an active carbon sink or emission source except for a few pixels in upper parts of Pakistan and India along with Nepal and Bangladesh under both transient and fixed land-use (Figure 4.4). These carbon sources are minimal in comparison to the carbon sink in their surroundings. As for the land-use changes in the past period, the calculation of the simulated data indicates no land-use changes for the time period of 1851-1880.

In the present period the area of the region acting as carbon source is increasing under both transient and fixed land-use and so are the carbon sinks indicating a higher Net Biome Productivity as compared to the past period as a result of increased anthropogenic activities. The calculated land-use change for present period indicates changes in the bio-physical characteristics of the land in some areas in the region. The areas that experienced land-use changes are acting as both carbon sinks and carbon sources. The areas acting a carbon source are mostly found in upper parts of Pakistan and India, the coastal line of India along the Bay of Bengal is also acting as a carbon source a small part of Sri Lanka is an active carbon emission source as well for the present period.

When compared between the transient land-use between past and present period figure 4.4 indicates and intensive increase in the Net Biome Productivity of the region with more area as an active sink or source of carbon emissions.

The Net Biome Productivity under RCP 8.5 for the future period indicates a high net carbon sink with very few indicators of carbon source (Figure 4.4). The Net Biome Productivity of South Asia is lower in the future under RCP 8.5 as compared to the present period which is an indicator of decline in the vegetation cover in the region, but the carbon sources are even lower than that of carbon sink in the future. The carbon sinks are higher as compared to the carbon sources in the future due to denser vegetation in some areas of South Asia but the spread of the vegetation has decreased in comparison to the present period. The dense vegetation is indicating an increase in atmospheric carbon concentration and facilitating plant growth through the process of carbon fertilization (Blumenthal et al, 2013).

The Net Biome Productivity in the future under RCP 2.6 has also decreased in caparison to the present period. Under RCP 2.6 the vegetation clusters are less dense as compared to RCP 8.5 and there are almost no carbon sources as it is assumed that under the ideal scenario i.e., the emission sources will be shifted towards sustainable sources and carbon capture techniques will be applied and is the pathway towards the future with the lowest possible concentration (Sanford et al, 2014). Under RCP 2.6 the atmospheric carbon concentration is lower as compared to the RCP 8.5 hence less denser clusters of vegetation are present under this scenario in the future.

4.4 Temporal Trends in NBP of South Asia

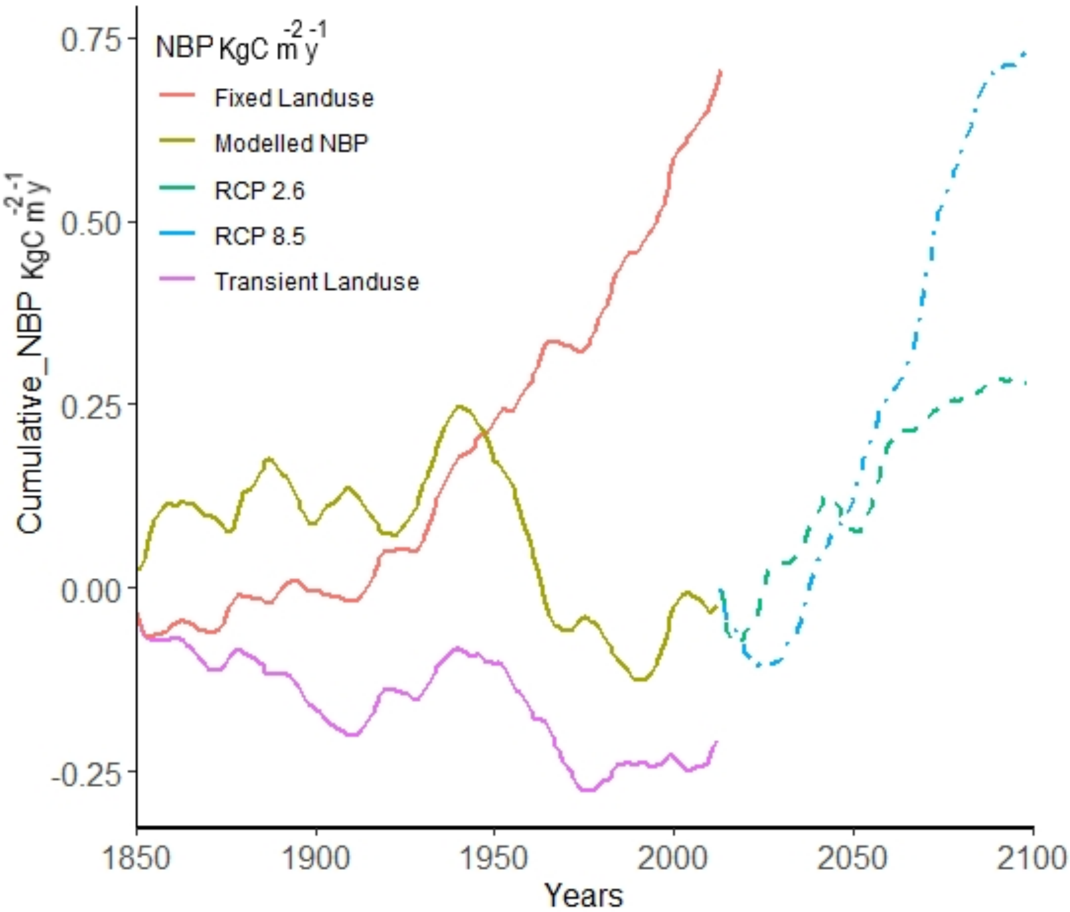


Figure 4.5: Cumulative Net Biome Productivity of South Asia

The Cumulative NBP for the historical period (1850-2012) the NBP is represented under both transient and fixed land-use. Under fixed land-use the NBP is higher as compared to transient land-use because land-use change is excluded from the fixed land-use. Under transient land-use the NBP is lower because of the changes in the land-use. Modelled NBP for the historical period is higher in the past with a sharp decline in 1930's.

Under the scenario phase (2013-2100) the NBP of South Asia is higher under RCP 8.5 which could be an indicator of increased productivity under RCP 8.5 as compared to RCP 2.6 where the NBP is increasing for the last half of the century with the increase getting more linear in the last two decades (Figure 4.5).

The trend in the NBP of South Asia was analyzed for years 1961-2012 to better understand the carbon flux of the region for the period. The trend was analyzed by using Mann Kendall test under both fixed land-use and transient land-use. The NBP trend under fixed land-use indicates slightly lower NBP as compared to transient land-use (Figure 4.6).

4.4.1 NBP flux for Fixed Land-use

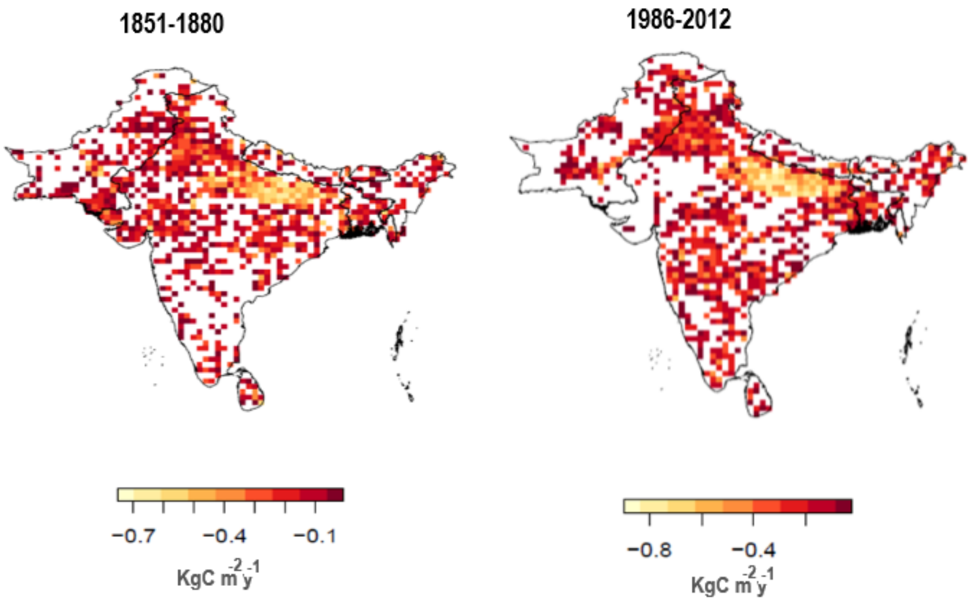


Figure 4.6: Net Biome Productivity flux under Fixed Land-use for past and present period.

Under fixed land-use the NBP is lower, the low NBP under fixed land-use is a result of excluding agricultural emissions from the fixed land-use simulations which indicates that without anthropogenic agricultural emissions the NBP of the region would be higher. In figure 4.6 most region has a positive correlating trend in terms of the NBP except for a small region in India that has lower correlation and is representing a decline in the NBP in the region. There are more negatively correlating data points and are scattered throughout the region among all the countries in the study area.

4.4.2 NBP Flux for Transient Land-use

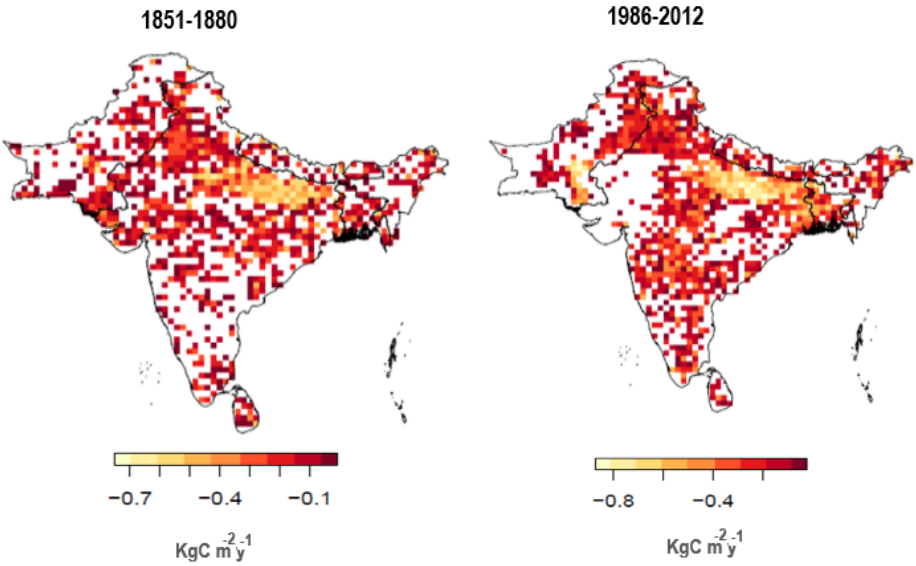


Figure 4.7: The Net Biome Productivity Flux for Past and Present Period under Transient land-use

The NBP under transient land-use is higher as compared to NBP trend under fixed land-use. The high NBP under transient land-use is a result of including anthropogenic agricultural emissions in the simulations. The NBP trend has a high correlation especially in the past period with a decreasing trend in the present period. The slightly lower flux in some parts of the region is an indicator of reduced carbon exchange between the atmosphere and the terrestrial ecosystem which could be an indicator of anthropogenic involvement including human settlements or industrial development, etc.

4.5 Correlation between Modelled Land-use Changes and Observed Carbon dioxide Emissions

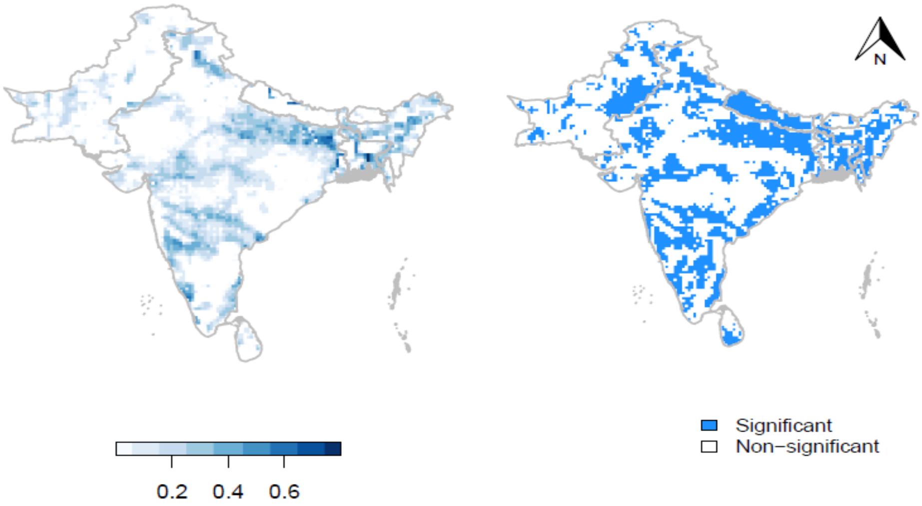


Figure 4.8: Correlation between Modelled Land-use Change and Observed Carbon dioxide Emissions for Years 1960-2012.

The modelled data for LUC was correlated using Mann-Kendall test with the observed carbon emissions to analyze how much of the impact LUC has on the carbon emission of South Asia. The observed data was acquired from the Regional Emission inventory in Asia (REAS) (REAS, 2021). The correlation for carbon emissions and LUC is mostly a very negative correlation for years 1961-2012 (Figure 4.8). There are some data points that indicate a positive correlation as well. The significance of the correlation was calculated using p-values (<0.05). The significance of the positive correlation is low. The correlation is indicator of the fact that most of the carbon emissions in South Asia are a result of anthropogenic activities other than LUC while there are some areas that have high carbon emissions as a result of LUC activities (Figure 4.8).

4.6 Yield of South Asia

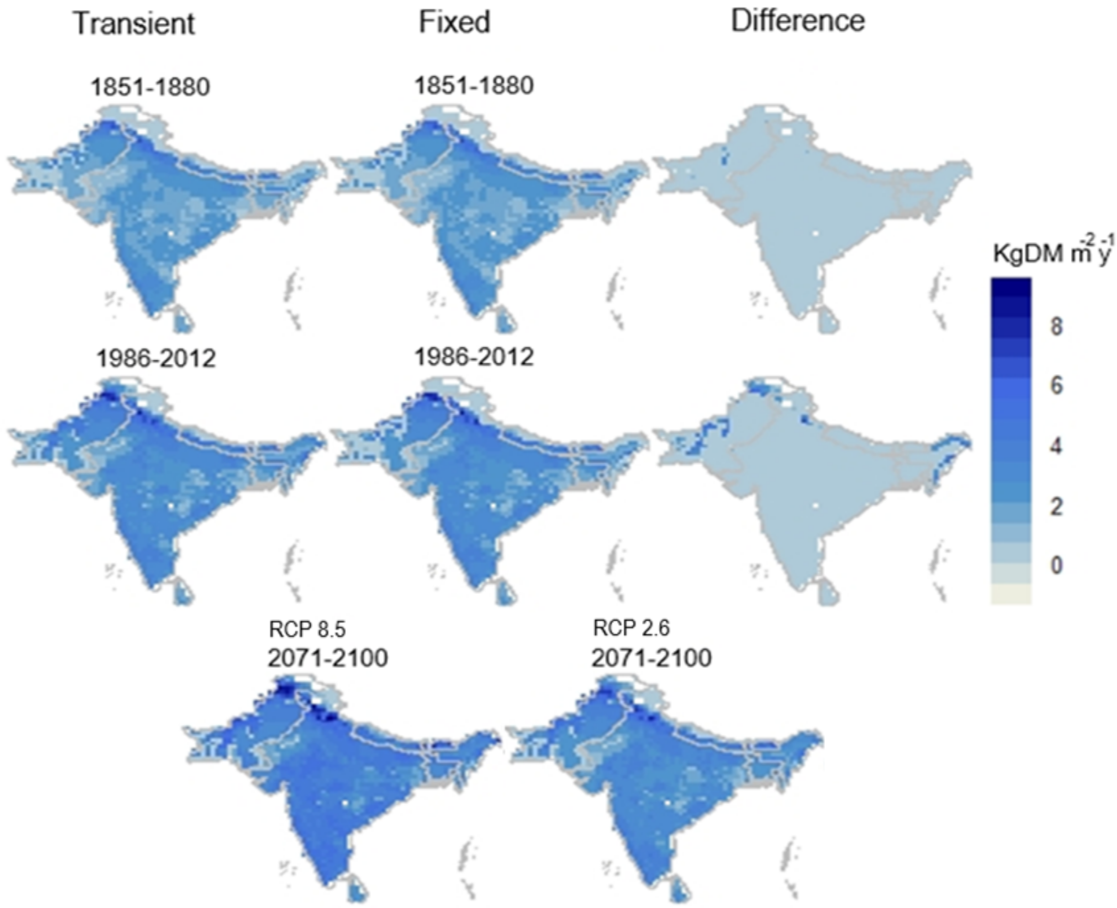


Figure 4.9: Spatial Patterns in Yield of South Asia for Past, Present and Future Periods.

The differences between transient land-use and fixed land-use were calculated for the past and the present period to under the land-use changes associated with agricultural production for their respective time periods.

In the past under transient land-use there is a significant amount of yield spread across the region which is higher as compared to the yield under fixed land-use (Figure 4.9). The reason behind higher yield under the transient land-use is increase in land-use and land cover. Under the fixed land-use the agricultural production is significant and just slightly lower compared to the yield under transient land-use (Figure 4.9). The reason why the agricultural yield is lower under the fixed land-use is that the land-use is fixed at the year 1850 emission levels and there are no changes in the land-use to keep up with the demands of human need. The difference calculated between transient and fixed land-use for the past period indicates almost no land-use changes for that time period except for a very small region in the Baluchistan province of Pakistan.

In the present period between years 1986-2012 the yield has increased significantly under both transient and fixed land-use with denser clusters in Khyber Pakhtunkhwa (KPK) in Pakistan and Punjab India as well (Figure 4.7). In terms of land-use change for the present period there are none spread across the map except for Baluchistan and Khyber Pakhtunkhwa Pakistan, slight changes in Punjab India along with some area near the coast line in Bangladesh and eastern India.

In the future the yield is increasing under RCP 8.5 with very dense clusters in KPK Pakistan and Punjab India and there is a wide spread of yield across the map in South Asia (Figure 4.7). The reason behind the increase in the yield is a result of carbon fertilization (Najafi et al, 2018). Under RCP 2.6 the yield is declining as compared to the present period and is lower as compared the RCP 8.5 as well. The decline in the yield under RCP 2.6 can be explained by the fact that the effect of increased carbon concentration is not impacting the yield as it is the lowest concentration pathways and carbon emissions as a result of anthropogenic activities are reduced by the application of carbon capture techniques.

4.7 Temporal Trend in Agricultural Yield of South Asia

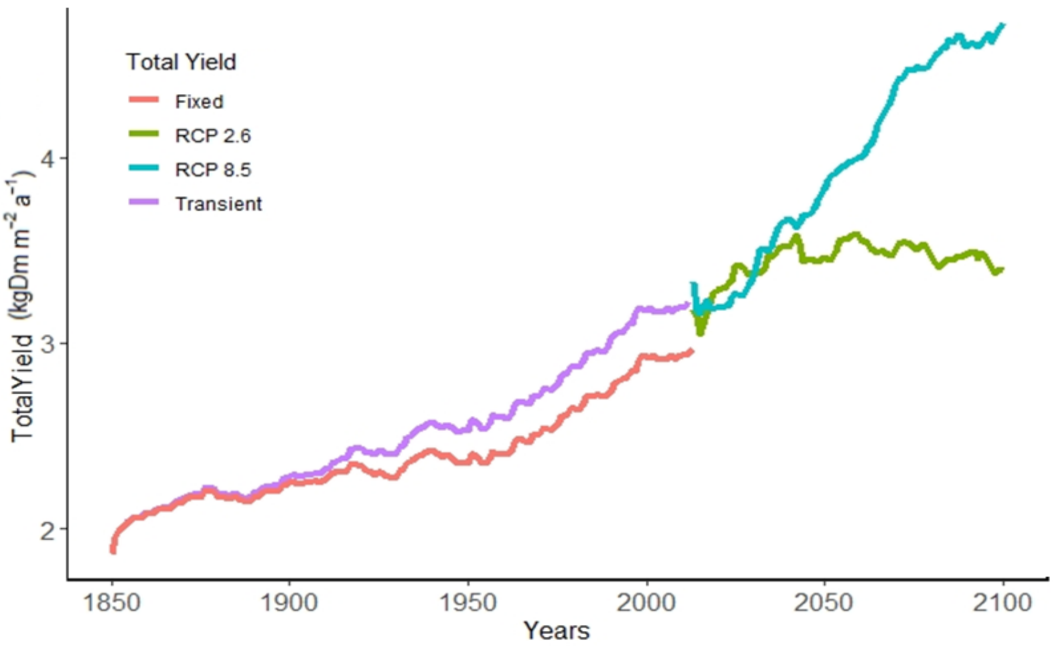


Figure 4.10: Temporal Trends in Yield of South Asia.

The temporal trends in the agricultural yield in South Asia were analyzed in two phases (Figure 4.10):

I. Historical Phase: 1850-2012

II. Simulation Phase: 2013-2100

Historical phase was analyzed under two different land-use scenarios:

I. Transient Land-use
II. Fixed Land-use

As for the simulation phase it was analyzed under two RCP's:

I. RCP 2.6: The ideal scenario
II. RCP 8.5: The extreme scenario

In the historical phase the transient land-use scenario has a higher trend as compared to the fixed land-use scenario. The higher trend under the transient land-use is due to increase in the agricultural practices and increased land-use change activities. The trend under the fixed land-use is lower because the LUC practices are fixed at 1850 levels so the increase in the trend is not as extensive as compared to the transient land-use scenario.

For the simulation phase the yield is increasing initially for RCP 2.6 but starts to decline around the 2040s (Figure 4.10), the decline in the yield is an indication of limited vegetation growth from a lower atmospheric carbon concentration as well as an exhaustion in the soil nutrient levels. On the other hand, the trend under RCP 8.5 is increasing drastically with a very rapidly increasing trend throughout the scenario phase. The rapidly increasing trend under RCP 8.5 is attributed to increased atmospheric carbon concentration which results in carbon fertilization to support plant growth. The impact of carbon fertilization is higher on vegetation in higher altitude as compared to the low altitudes (Mendelsohn & Massetti, 2017).

4.8 Comparison between Modelled and Observed Yield.

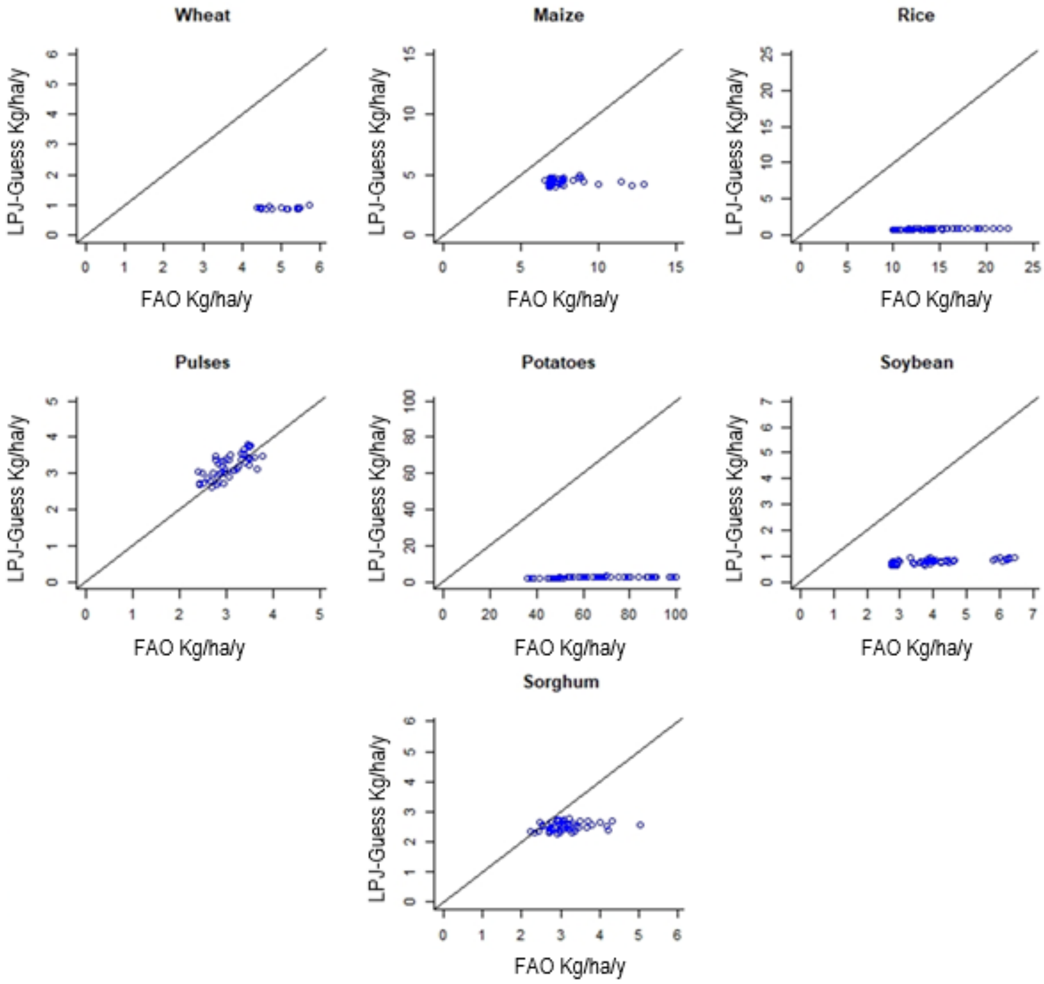


Figure 4.11: Comparison between Modelled Yield and Observed Yield for Years 1961-2012.

In order to calculate the accuracy of LPJ-GUESS to simulate crop yield, the modelled data was compared using the identity line with data acquired from Food and Agricultural Organization (FAO) (FAO, 2021). LPJ-GUESS modelled data of 7 major crop types of South Asia including Wheat, Maize, Rice, Pulses, Potatoes, Soybean and Sorghum were compared with the data available at FAO.

For wheat, the observed yield is increasing gradually while the modelled yield has none to no increase in comparison. When both data sets are compared, no correlation is shown among the data sets (Figure 4.11). Maize yield is higher in comparison to wheat for both modelled and observed data sets but observed and modelled data does not correlate to each other when correlated using the identity line (Figure 4.11). Rice yield for observed data is higher than both maize and wheat while the modelled data is lower than both other crops. There is no correlation between observed and modelled rice yield (Figure 4.11). The modelled data for pulses corresponds with the observed data for pulses and falls exactly on the identity line indicating a correlation among the two data sets (Figure 4.11). The modelled data for potatoes indicates no changes in the yield while for the observed data the yield is increasing significantly, in fact potatoes have the highest observed yield among all the crops. The modelled data does not coordinate with the observed data hence shows no correlation and falls under the identity line. For Soybean there is a slight increase in the yield for modelled data and an increase in the observed data as well. The modelled and observed data does not correlate and falls under the identity line. Some of the data in case of sorghum falls on the identity line showing a small correlation between observed and modelled yield. Most of the data points fall under the line for sorghum as well.

The reason behind low correlation between modelled and observed yield data is that the modelled yield was not calibrated.

Chapter 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The spatial and temporal analysis of LPJ-GUESS simulations for NBP revealed that the NBP will remain constant in the future under RCP 2.6 and will experience a slight decline under RCP 8.5 as a result of extensive LUC. If the LUC remain constant then the NBP will increase which is indicated by the PNV simulations under both PNV 2.6 and PNV 8.5. The NBP trends of the present period (1961-2012) indicate an increasing trend under both fixed and transient land-use.

The analysis of spatial and temporal patterns in yield indicates an increasing trend with a very drastic increase in the yield under RCP 8.5, which is an indicator of carbon fertilization and enhanced photosynthesis rates. The yield trends for the present period also indicate a very positive increasing trend in the yield.

LUC are expected to increase under both RCP 2.6 and RCP 8.5. under RCP 2.6 the LUC are acting more as carbon sink while under RCP 8.5 there's a dramatic increase in the sources of carbon emission. The correlation of LUC with the observed carbon dioxide emissions for the present period indicates that the sources other than LUC are responsible for most of the carbon emissions in the present.

In order to validate the yield prediction of LPJ-GUESS the modelled data was compared with the observed data from FAO which revealed a large yield gap between two data sets.

5.2 Recommendations

The results of this research indicate that South Asia is a net carbon sink and will remain to be a net carbon sink in the future as well. There's and uncertainty in the sink capacity of South Asia as the demand to keep up with the increasing population is also increasing. The agricultural yield is also uncertain. Following are the recommendations based on this study:

I. In order to integrate the findings of research at policy level and prioritize agricultural management practices along with mitigation practices, there is a need to develop regional DVM's.

II. The development of policies at regional levels to better cope with the impacts of climate change on agricultural sector and to be able to mitigate them.

III. Integration of missing processes in the DGVM's, such as nutrient availability, fertilization and disease.

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