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Maximilian Lackner
Baharak Sajjadi
Wei-Yin Chen
Editors

Handbook of Climate Change Mitigation and Adaptation

Third Edition

Springer

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With 1088 Figures and 347 Tables

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To Konrad Steffen (2 January 1952–8 August 2020), a Swiss-American climate scientist who died on a research field trip to Greenland, when he fell into a crevasse. Before deglaciation, such crevasses were not known.
To the 5 million people, whose annual premature deaths are linked to climate change already now.
To those who will take action in the future to combat climate change, for all of us.

Foreword

The first two editions of this *Handbook* have already established it as an essential tool for the increasing number of theoreticians and practitioners working in the overlapping fields of the climate and life sciences, socio-economics, engineering, and even aesthetics and philosophy. The first edition had 2130 pages, 586 figures, and 205 tables; the second one 3331 pages, 1108 figures, and 352 tables.

This third edition is clearly even bigger and better. As we get ready to plunge into it, it is worth stopping for a moment and reflecting on the evolution of what has become an important field of and onto itself, namely, that of *Climate Change Mitigation and Adaptation (CCMA)*. This foreword dwells on three important topics for this field: (i) the communication problems of interdisciplinarity; (ii) the crucial role of the times in which we live for the future of humanity on this planet; and (iii) the impact of stakeholders on the science we conduct.

To start with (i), it is well known that living at or near a border is potentially very interesting but it is often also quite difficult. This statement is especially true in the sciences, where speaking a different language makes mutual understanding harder, as does having grown up with an often very different type of education. Ludwig Wittgenstein already pointed out the difficulties involved in communication among different "language communities," into which he definitely included scientific communities.

It is thus important to keep in mind, as CCMA develops its own language, that this language should be rich and creative in and of itself, but also draw on the neighboring languages of the separate communities that have contributed to its birth and are continuing to nurse it. To put this less philosophically and more concretely, Integrated Assessment Models (IAMs), as an important dialect of the new CCMA language, need to balance the requirements of both climate and economic modeling: the former deeply anchored in a physical language, in which the basic rules are natural conservation laws, the latter in a socioeconomic language, in which the rules are more empirical and consensus-driven but equally important.

There is, however, a truly striking case of a phrase jumping the language barrier; that phrase is "tipping points." Sudden jumps from one steady state of a system to another were originally studied by Leonhard Euler, three centuries ago. Euler formulated and solved a mathematical model for the buckling of a beam, i.e., for its sudden transition from a straight to a curved state, as the axial load on it is increased past a critical value. Such a transition became known as a *bifurcation.* Bifurcations were generalized in the mid-twentieth century from saddle-node bifurcations between two steady states to Poincaré-Andronov-Hopf bifurcations between a steady state and a cyclic behavior and, in the later twentieth century, to various forms of transition between periodic and chaotic types of behavior, dubbed routes to chaos.

Unaware of this rich history – which involved applications of bifurcation theory to a plethora of problems in the physical, biological, and even socio-economic sciences – a journalist, Malcolm Gladwell, had the intuition that such sudden transitions due to "little things," like a small change in a parameter value, could play a big role in sociology. His book, published in 2000, became a bestseller and the phrase took off. Tipping points are now everywhere, and they have even been given a precise mathematical definition as bifurcations in dynamical systems subject to time-dependent forcing. Relevant examples are the bimodalities in sea ice cover of the Arctic and in the vegetation cover of the Amazon basin; in both cases, the time-dependent forcing to be considered is the anthropogenic change in atmospheric composition and, hence, optical properties.

Turning now from mere linguistics issues to Earth- and humanity-shaking ones, the realization that we are at a crossroads is truly sinking in. The 2020s decade that just started has already been called the "Soaring Twenties," a wink to the post-WWI "Roaring Twenties." It is a decade that, by most accounts, will play a key role in the coevolution of humanity and its planet. While there is still no dearth of incredulous or uninformed people – in countries large and small, advanced and developing – the overwhelming consensus of informed opinion is that we have to change our spendthrift collective ways and do something to prevent the young generation and the following ones from suffering greatly.

But what exactly do we have to do about climate change? CCMA, as a field of science and engineering, has a lot to contribute to the multiple answers to this question. These answers need to also take into account that there are many other issues involved in humanity's current and future well-being than climate change: loss of biodiversity is due to human population pressure and not just to climate change; regional and social inequalities affect and are affected by climate change, and so on and so forth. One rapidly emerging fact is an increasing commitment from the giants of private business to chart a course that aligns with the approximately right direction of achieving "net-zero" carbon emissions by mid-century or earlier. Another such fact is the rapid emergence of "green finance" and, more generally, of investment that is driven by, or at least affected by, so-called *environmental*, *social*, *and governance (ESG)* criteria.

Up until recently, the efforts of climate and environmental activists and of their large crowds of followers have focused on convincing public decision-makers to deploy the means of states and international institutions in support of the requisite steps for a better future. More recently, the resources of both public and private finance, to the tune of tens of trillions of dollars, are seeking environmentally sound investments to maximize growth and mitigate risk, and the private portion is much larger than the public one. The risks incurred by such investments are transitional – i.

e., those associated with mitigation policies – as well as physical, such as asset losses due to climate change and variability. Still, the increased private-capital interest appears to be going, more and more, beyond “greenwashing” and on to real action.

And here we are getting to the third and last part of this foreword. Most private institutions, including the largest ones, do not have the same experience with fostering science in support of their goals as public ones do. Maximizing an investment bank’s growth and mitigating its risks might not always harmonize with the lofty goals of saving the planet and optimizing humanity’s life on it. Just to give one small example, private capital is much more in tune with the traditional measure of national and global success, namely, gross domestic product (GDP). But it has become clearer and clearer that GDP is not the unique and not even a good measure of individual or community happiness.

Over the last decade, it has been forcefully argued that the Inclusive Wealth Index (IWI) is much better at measuring welfare and not just production. It is important, therefore, to use IWI and, possibly, other multi-index measures in projecting the state of the world into the future, no matter what certain powerful stakeholders in this future might think.

A final scientific point concerns the uncertainties in such projections. It is these uncertainties that must be taken into account in deciding “what exactly do we have to do?” Beyond the well-known, and multiply attributed, saying about “the known unknowns and the unknown unknowns,” there’s not much one can do about the latter. But there are many ways to take into account the former. Uncertainty quantification has become a flourishing field in the sciences and engineering. The financial industry has, obviously, its own ways of quantifying uncertainty – ways which are quite sophisticated and well adapted to its purposes but are quite different from those that are used in the climate and ecological sciences. Once more, there’s a language problem, and we’re back to the first topic on our list.

The topics that were touched upon in this foreword are, naturally, just three out of many. I can only wish this *Handbook’s* third edition all the success it deserves and hope that some heed will be paid to these topics in future editions as well.

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Michael Ghil

Preface

The third edition of the Handbook, printed 10 years after publication of the first edition, has arrived. Meanwhile, the Keeling curve has moved from 394 to 419 ppm, and evidences of the devastating climate changes have emerged, such as the complete loss of stability of the natural Atlantic Meridional Overturning Circulation (AMOC) (Boers 2021). We have also learned more about climate change and mitigation, which will be the emphasis of this edition. But what is in knowledge?

"The more I know, the more I realize I know nothing." Socrates

"The more I learn, the more I realize how much I don't know." Albert Einstein

With more knowledge also come uncertainties, and science needs to and does look at them. Climate change has been a political topic ever since. The oil lobby has been accused of denying climate change. A notorious memo from 1998 reads: "Victory will be achieved when average citizens recognize uncertainties in climate science" (https://www.govinfo.gov/content/pkg/CHRG-116hhrg38304/html/CHRG-116hhrg38304.htm, accessed August 8, 2021). It is not that simple, though, to merely demonize one industry. Climate change, this is all of us. And victory can be for no one.

Today, "sustainability" has become somewhat of a hype. Be it circular economy, meat consumption, energy use, resource consumption, carbon emissions – the feeling has emerged that both organizations and private citizens all over the planet have started to recognize that something with the current way of living is wrong. But do we see countermeasures or a changing trend? The COVID 19 pandemic was an unprecedented caesura, yet its effect on our climate is estimated on only 0.01 °C of avoided warming (https://www.bbc.com/future/article/20210312-covid-19-paused-climate-emissions-but-theyre-rising-again, accessed August 8, 2021).

This Handbook makes a contribution by offering an up-to-date, comprehensive collection of knowledge on climate change adaptation and climate change mitigation.

It is up to you, the reader, to take this knowledge and put it into action.

The editors of this Handbook want to thank all authors for sharing their research, and the publishers for enabling this format. The next decade is definitely a decisive one for our climate. Let us all act within our own sphere of influence. Like every molecule of CO_2 counts, it is every step, large or small, in the right direction that is of value, and remember that the first steps are always the most important ones.

April 2022 The editors

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Prologue

Climate change is a global issue that will affect all of us. Its negative effects have already begun and are felt on all parts of the planet, from the poles to the equator.

The concept and theory of the greenhouse effect have been described and studied for almost two hundred years, and the question of whether or not our anthropogenic activities affect the climate has been asked and answered for almost as long. Since the second half of the twentieth century, it has become apparent that we humans cause the climate to change due to modern societies' emissions of greenhouse gases, and now the science is clearer than ever. The climate is changing rapidly due to our human activities. If we do not address this issue and immediately act on mitigating it, the consequences will be potentially devastating. We can no longer ignore the facts.

Scientists studying climate change and its effects have called out for change and action for decades. They have warned the public, governments, and companies that we need to act, and that we need to act now.

However, for some reason, these warnings have seemingly passed unheard. Despite scientists urging for climate action, little has happened. Now, in the last few years, climate change has risen substantially on the international agenda. Apart from the few denying climate change, the majority agrees that something needs to be done. Still, large-scale action is yet to be seen. It seems as though society is paralyzed. Action from politicians, financial leaders, and others with the power and mandate to enact action is yet far too slow and far too little compared to what needs to be done.

The current inaction toward climate change could be described as though we are performing a collective global experiment on our earth's climate, with both nature and ourselves as the metaphorical guinea pigs. This being said, all is not yet lost. Science does not only tell us what the issue is and where it stems from, but also provides us with the tools and insights necessary to resolve the problem of anthropogenic climate change. So, to stop this enormous high-stake gamble with our planet, its ecosystems, as well as our own lives and futures, we need to collectively act and demand real, sustainable climate action from those with the economic and political mandate to enable large-scale change. With said change being rooted in science, democracy, and sustainability. It is not an impossible task, but it is a necessary one.

The climate crisis is a global crisis, and it is time to act accordingly. Listen to the science.

Alexander Ahl, Isabelle Axelsson, Alde Fermskog, Ell Jarl, Greta Thunberg

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About the Editors

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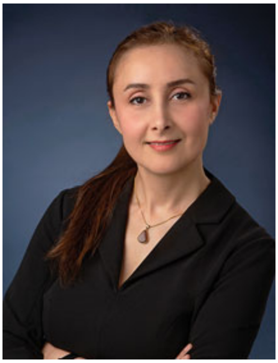

Dr. Baharak Sajjadi is an assistant professor of Petroleum and Geological Engineering in the Mewbourne College of Earth and Energy at the University of Oklahoma, USA. She has obtained her PhD in chemical engineering from the University of Malaya, Malaysia, in 2015, and has served as a research assistant professor of Chemical Engineering at the University of Mississippi, USA. She has over 10 years of research experience in advanced refinery processes and bioprocesses, carbon conversion and modification technologies, renewable energies, and computational fluid dynamics

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Dr. Wei-Yin Chen is a professor emeritus of Chemical Engineering of the University of Mississippi. He has had over 40-years of experience in developing technology-driven, knowledge-based, carbon conversion programs for in-furnace NO reduction, coal liquefaction, and low-temperature carbon modifications for sustainable food, energy, and water nexus. He founded and has been leading the Sustainable Energy and Environmental Group (SEEG) with over 250 collaborators around the globe. The SEEG pioneered the use of ultrasound, light, non-thermal plasma, biological, and chemical methods to modify the material surface for carbon gasification, carbon activation for CO_2 capture and wastewater treatment, soil amendment, electrode fabrication, desalination/deionization, biomedical material, fuel cell, etc. He has been awarded by UM and national and international organizations for his contributions to research, teaching, and services. He has served as a reviewer or panelist for institutions around the globe.

Natural Resource Management and Sustainable Agriculture

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A. I. Obaisi, M. J. Adegbeye, Mona M. M. Y. Elghandour,
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Abstract

In this chapter, we explore the impacts of agricultural practices on the properties of the soil, discussing conservation tillage, crop rotation (see below), etc. This chapter further discusses the need for conservation tillage outlining benefits such as reduction of topsoil erosion and runoff, and carbon sequestration. It carefully explains how conservation tillage is a climate-smart soil management practice.

In the face of a geometrically rising global population, how do we face the looming food security challenge? This chapter discusses how we can engage Sustainable Livestock farming to ensure food security meeting dietary protein requirement. In this chapter, several have been pointed out on the impact of sustainable agriculture on global warming and climate change. Such technique includes climate-smart farming, giving less human edible to animals, implementation of efficient, eco-friendly, and adaptive animal agroforestry, silvopastoral farming, less or zero tillage, sustainable crop production systems/practices, nutrient and fertilizer management, incorporation of renewable energy into farming, integrated watershed management, anaerobic digestion, and climate and weather information systems. Despite the variation of these techniques, the impact of their application centers on climate change adaptation and mitigation, carbon sequestration, reduction of greenhouse gas emissions, and reduction of environmental pollution caused by agriculture. This chapter shows that if these sustainable techniques are applied, more yield will be derived per unit of limited agricultural resources such as land, nutrient, and water, and less emission will be released into the atmosphere per unit of yield derived, etc.

Keywords

Conservation · Livestock · Land · Mitigation · Natural resource management · Soil · Sustainable agriculture · Watershed management

Introduction

What Are Natural Resources?

Natural resources are resources that come from the natural environment and can be harnessed to meet the needs of man and other living things. Common examples of natural resources are air, water, land, natural gas, wood, oil, coal, etc.

What Is Natural Resource Management?

Natural resource management can be explained as the judicious use of resources found in the natural environment in a manner that does not jeopardize the future generations harnessing same resources to meet their needs (Iyyanki and Valli 2017). These resources provide mankind with the necessities for quality life through the natural ecosystem. The needs and demands of the rapidly increasing human population from the finite and limited natural resource base have brought to the fore the urgent need for natural resource management to ensure the continuity of humans. The abnormal use and overexploitation of these natural resources beyond earth's *carrying capacity* has raised serious concerns in recent times. Natural resource management and effective governance of natural resources has always been considered vital, but now, the clamor for the efficient management of these resources is getting louder in the face of climate change, market demands, modernization, and population explosion. The complexities involved in the efficient management of these natural resources have made it a daunting task. The alarming rate of depletion and pressure on natural resources is threatening the quality of land, forest, and water, and the ability of these resources to replenish themselves at the rate at which they are being exploited. Globally, the sustainability of natural resources is faced with serious *threats of loss and extinction*. Conflicts are beginning to arise over these resources; there is a dilemma between preservation and utilization of these natural resources. The economic values of these natural resources and the political interests vested have further made the management of these resources in the natural environment increasingly difficult.

Natural Resource Management and Sustainable Agriculture

The agricultural sector is a very vital one in the global economy; it does not only provide food, but it also provides jobs, raw materials, etc. Agriculture involves crop and animal production, and these make use of natural resources. There are certain factors for crop and animal production, and these include land, labor, capital, etc. Land, just as the other factors of production, is essential for both animal and crop production, and its management determines how long it can serve the needs and demands of the growing population optimally. A major part of the world's arable lands is being used or has been exhausted due to unsustainable practices and is no longer productive (Pimentel and Pimentel 1996). The previously productive and fertile lands have now become degraded. The rate of degradation of lands globally has been accelerated by the climatic changes coupled with excessive use of inputs to maintain or increase yield levels (UNEP 2018).

Commercial agriculture heavily relies on inputs such as pesticides and fertilizers most of which finds its way back into the environment through leaching or runoffs adversely affecting the environment. For instance, in the year 1998, it was estimated that 137 million metric tons of chemical fertilizers was used globally (FAO 1999), and only one-third of the applied nitrogen is taken in by the plant/crop (Tilman 1998). This excess nitrogen can adversely affect plant diversity and in the environment can lead to major biodiversity loss such as decline in insect and beneficial bird population. This might lead to an upset in the prey-predator balance, and also the runoff can pollute groundwater and surface waters. Chemical fertilizers used on farmlands overtime raise the acidity level of the soil and ultimately stunt or prevent plant growth (Barak et al. 1998).

In the light of the above, sustainable agriculture is the way out, ensuring food security and preserving natural resources. In recent times, agriculture practiced on industrial and commercial scale is termed unsustainable as it continues to use up and degrade natural resources quicker than nature can replenish them. One of the aims of sustainable agriculture is to encourage cultivation systems and farming practices that mitigate the impacts of harmful unsustainable practices to the natural environment (see below). Sustainable agriculture recognizes that natural resources are not infinite and, therefore, encourages limits on economic growth drives while clamoring for fair resource distribution. Sustainable agriculture has the following objectives such as conservation and preservation of the environment, overall growth and development of the economy, and social fairness and justice. The whole sustainability discussion is based on meeting the needs of the present without jeopardizing the ability of the future generations to meet their own needs (Fig. 1).

The image above shows results of the GLADIS approach used to monitor the status and trends of land degradation and the demand pressures on ecosystem services.

Urgent Need to Adopt Sustainable Agriculture

Top on the list of challenges bedeviling the world now is how to meet the needs of the geometrically expanding population without exhausting natural reserves through sustainability for the sake of future generations. According to FAO (2009), this need will put immense pressure on arable lands for food production and other natural resources. Today, we are faced with the effects of climate change such as drought, floods, and also with changing socioeconomic conditions (emigration of youth to urban areas). Sustainable farming has become the likely option as the demand of the rapidly growing population continually drives wrong practices. We will explore alternative sustainable options as we proceed in this chapter.

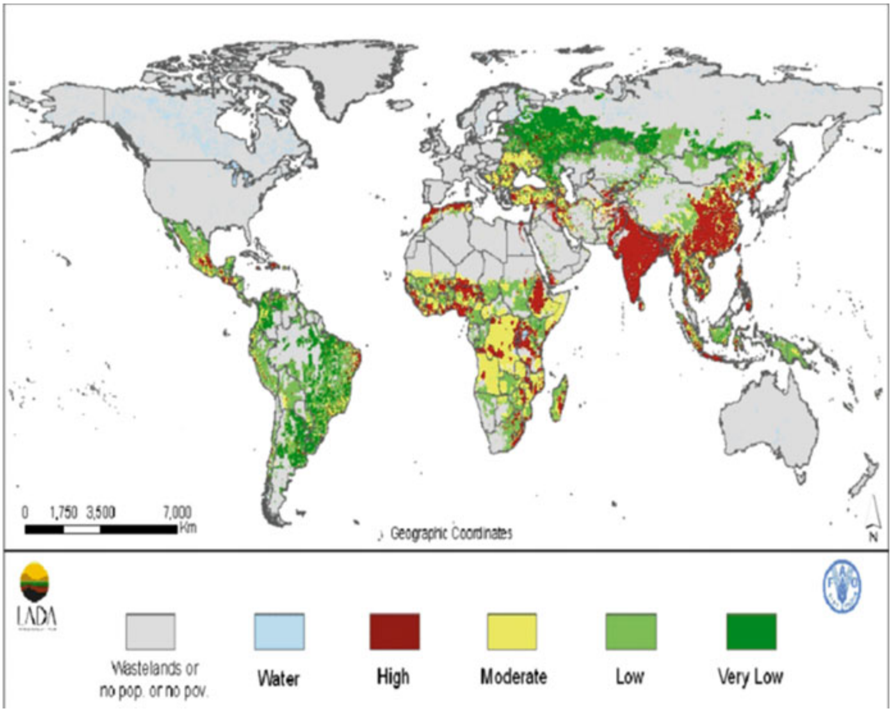

Fig. 1 Map showing land degradation index across the world. (Source: Nachtergaele et al. The harmonized world soil database. In Proceedings of the 19th world congress of soil science, soil solutions for a changing world, Brisbane, Australia, 1–6 August 2010)

The need to achieve food security urgently requires pinpointing soil management systems that sustain crop yields and outputs while at the same do not negatively impact the environment. It also involves adopting sustainable livestock management strategies that mitigate climate change and meet nutritional requirements. In the bid to meet demands for food, a lot of wrong practices are engaged to hasten crop and animal production that negatively impact the environment. These inputs have severe consequences.

Climate Change, Carbon Dioxide Emissions, and the Need for Sustainable Agriculture

Climate change is known to be caused by several climate pollutants with the largest three individual contributors being carbon dioxide, methane, and nitrous oxide (Myhre et al. 2013). Food production and agriculture have a strong relationship with these three key contributors to climate change with the predominant two contributors from agriculture being methane and nitrous oxide.

Global food production takes responsibility for about 21–37% of global yearly emissions. It is the activities involved that are responsible for these emissions; therefore, it is important that to address the contribution of agriculture to climate change, attention should be paid to the systems and techniques adopted in crop and livestock production.

It remains difficult to quantify the amount of carbon dioxide contributed to climate change from agricultural production due to the processes through which the emissions are generated. Some of the ways in which agriculture contributes to climate change are application of lime and urea to the soil, carbon dioxide from machine operations and energy consumption (such as tractor fuels), agricultural inputs (fertilizers, etc.), and transportation (Vermeulen et al. 2012). The preferred channel to overall reduction of emissions from the agricultural sector is the de-carbonization of power and energy production rather than individual agricultural mitigations.

Crop production remains one of the major causes of carbon dioxide emissions in agriculture as a result of land use changes emanating from repeated land clearing for animal and crop production. The net carbon-dioxide emissions generated from land use account for about 14% of the yearly anthropogenic carbon-dioxide (Le Quere et al. 2020) with 10% directly connected to agricultural activities.

Climate change which has been caused as a result of the changes in the average temperature of the earth has resulted in the following outcomes for agriculture:

- Lengthened time of cultivation season in temperate regions of the world
- Negatively affect crop production and yields in tropical regions of the world
- Increased rates of soil moisture evaporation
- Elongated and frequent drought periods

The impacts of climate change on agriculture will vary across different regions of the world. Therefore, it is difficult to determine in generic manner how climate change will affect all the areas of the world. Some of the reasons why this will be difficult are the following:

- Variation of distribution of diseases, pests, insects, and weeds
- Un-unified regional climate change prediction
- Uncertainty on possibility of adaptation of modern and climate-smart agricultural practices

Climate change impact on several regions will be dependent on physical, biological, and socioeconomic characteristics. In developing countries where most of the household are low-income households with the predominant population depending on rain-fed agriculture, they are more vulnerable to the impacts of climate change. Populations in these areas are susceptible to hunger and serious hardship. Food security challenges are most felt by the people in these regions of the world. Some of the adverse impacts of climate change on agricultural production are as follows:

- Reduced crop yields
- Reduction in amount of water available for crop and livestock production
- Reduction in land available for cultivation as a result of increased sea levels and flooding
- Increase cases of pest and disease outbreaks
- Salinization

Agricultural Practices and Greenhouse Gas Emissions

In order to reduce emissions generated from crop and livestock production, it is important that there needs to be a review of current production techniques and practices and exchanging them for more sustainable practices. There are several factors that come to play in the adoption of sustainable farming to address the impacts of climate change. Human population in recent years has witnessed geometric increase, and this has led to increased demand for crop and livestock, land fragmentation, land degradation, increased use of chemical fertilizers, and many more. For farmers to adopt sustainable farming, technological and government drivers are required to assist the farmers. In developing countries with limited access to modern farming systems and tools, most farmers depend on rainfall to grow their crops, and farmers in the bid to meet the food demands rapidly farm the same land year in and year out growing the same crop therefore making the land unproductive after some years.

Land preparation in developing countries is still predominantly bush burning which contributes significant amounts of carbon-dioxide to the atmosphere. Land preparation often in rural areas involves the cutting down of trees which have served has carbon sinks. As good as the thought of sustainable farming sounds, there is a difficulty we cannot overlook in the implementation and adoption of it among farmers who are profit oriented and in the face of skyrocketing demands of the world's rapidly increasing population. When it comes to livestock farming, when cattle graze, they belch releasing biogenic methane into the atmosphere. There has been a lot of clamors for people to switch to plant-based protein; still this has not reduced the demand for beef; therefore, the dilemma remains on how to seamlessly implement sustainable crop and livestock production all over the globe.

The Role of Carbon-Dioxide in Global Warming

Carbon-dioxide remains the largest contributor to global warming (Mhyre et al. 2013). For every ton of carbon-dioxide emitted, a worrisome amount of it stays in the atmosphere for prolonged periods (Archer and Brovkin 2008). The ability of carbon-dioxide to remain in the atmosphere for prolonged periods and accumulate is a major problem in our understanding of climate change. The above-explained concept makes us realize that net-zero emissions are beyond just an ambitious slogan, but it is a measure that needs to be urgently implemented to stop or at least slow down global warming through our knowledge of carbon cycle.

Carbon Sequestration

Carbon sequestration refers to a system where agricultural lands and forest areas serve as carbon sinks and storages, removing carbon-dioxide from the atmosphere. Plants and trees absorb and take in carbon-dioxide through the process of photosynthesis and store it in the roots, foliage, and tree trunks. Forests are popularly called carbon sinks because they can sequester large amounts of carbon in their root systems, tree trunks, and in the soil for extended periods of time.

Soils remain the biggest carbon storage location on earth. The ability of soils to sequester carbon is dependent on several factors, which include land use, vegetative cover, type of soil, etc. Human respiration and plant-decomposing biomass also contribute to the amount of carbon sunk in the soil. Through encouraging the adoption of climate-smart and sustainable farming practices that minimally disturb the soil, soils can sequester more carbon.

Opportunities for Mitigation Technologies and Practices in Agriculture

There are several mitigation opportunities in agriculture. Several will be discussed in this section:

Cropland Management

Since croplands are closely used and managed, it is feasible to implement mitigation technologies and measures in the areas of managing lands that are dedicated to crop production. Mitigation practices in crop management fall into the following categories.

(i) Agronomy – improved agronomic practices that promote harvest yields and lead to increased inputs of carbon residue have the potential to lead to increased carbon sequestration (Follett 2001). Examples of such practices include the use of improved crop varieties, elongated crop rotation, and reduction in cultivation of unplanted fallow (West and Post 2002). Emissions generated per hectare can also be considerably cut down by adopting cultivation systems that reduce dependence on fertilizers, pesticides, and other inputs, and a practical example of this can be seen in the rotation of leguminous crops (Rochette and Janzen 2005).

(ii) Nutrient management – a good percentage of nitrogen applied to crops in form of fertilizers is not efficiently used up by the crops (Galloway 2003). The excess nitrogen is likely to escape as emission into the atmosphere as nitrous oxide (McSwiney and Robertson 2005). Improving nitrogen use and efficiency can lead to reduced nitrous-oxide emissions therefore cutting down emissions from nitrogen fertilizers (Schlesinger 1999). An example of practices that improve

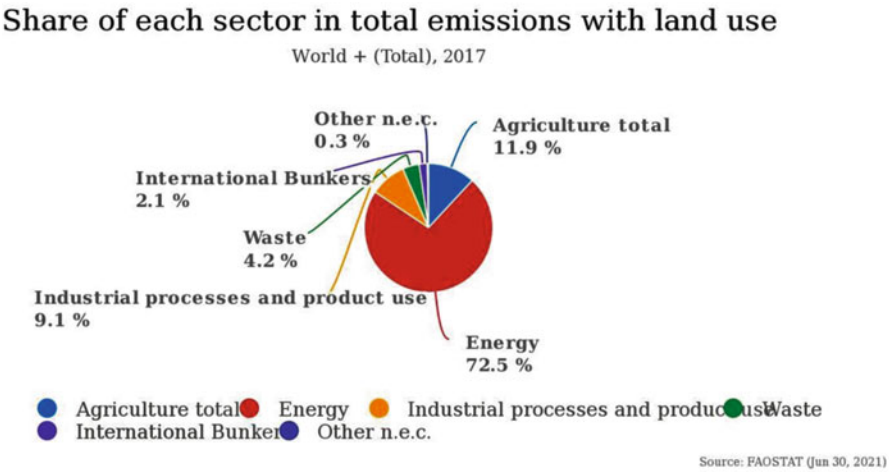

Fig. 2 Share of each sector's total emission with land use

nutrient efficiency is precision farming where the amount of fertilizer applied to crops is adjusted to be only what the crop needs. Another practice that can improve nutrient efficiency is improved timing of application of fertilizers. This involves applying fertilizer just before plant uptake (Dalal et al. 2003).

(iii) Land use change – it is a climate-smart strategy and practice to periodically change the crop cover on farmlands from time to time. Change of land cover can be entire or in part; nevertheless, this is encouraged as it increases carbon storage. For instance, converting an arable farmland into a grassland will lead to more soil carbon storage because of the reduced level of disturbance of the soil through cultivation activities. This also leads to reduced carbon loss through harvest (Paustian 1998) (Fig. 2).

Pasture and Grazing Management

It is interesting to know that grazing lands take more land than lands engaged for crop production (FAOSTAT 2006). Nonetheless, the grazing lands are not well managed like the croplands. Grazing leads to the release of carbon into the atmosphere, and cattle when they eat belch releasing methane, a very harmful greenhouse gas, into the atmosphere. There are several grazing systems and techniques that could be adopted in grazing to reduce emissions of greenhouse gases into the atmosphere as a result of grazing activities; these include the following:

(i) Grazing intensity – the intensity and timing of grazing can affect the rate of release and amount of carbon stored in the soil. It has been established that carbon sequestered in optimally grazed lands than there is in ungrazed and overgrazed lands (Rice and Owensby 2001).

(ii) Fire management – it is not an uncommon pasture management system to burn the bush to foster pasture growth for livestock grazing, but this practice contributes significantly to climate change in several ways. It leads to the release of methane into the atmosphere and produces smoke aerosols that can either warm or cool the atmosphere (Andreae 2001). Adopting a better grazing system that addresses fire management will reduce the frequency of bush burning.

Manure Management

Manure from animals can release significant amount of greenhouse gases into the atmosphere during their storage. The way to mitigate this is to ensure they are kept in lagoon water bodies, used for solid cover or by capturing the methane being released (Clemens and Ahlgrimm 2001). Emissions can be reduced significantly by keeping manure in solid form in liquid state. Manure management globally still tends to be difficult for farmers to manage as livestock excrete in the field, but more studies have been carried out to show emissions from excreted matter can be reduced when feeding systems are tweaked (Kreuzer and Hindrichsen 2006).

Increasing Agroforestry and Forest Reserves

Management of fires in forest reserves which serve as carbon sinks can significantly help to reduce the amount of emissions released into the atmosphere. More than ever, investing in agroforestry and tree planting will help to sink more carbon. Governments must intentionally work toward expanding forest reserves and incorporate tongyal farming where crops are grown alongside trees and the trees provide shade and their fallen leaves enrich the soil.

Sustainable Agricultural Practices

These include practices that are aimed at achieving optimal output while at the same time ensuring that the environment and other natural resources are not depleted hindering output and production in the future.

Conservation Tillage for Crop Production

Various agricultural practices have vital impact on the soil. Land clearing for planting severely impacts the soil environment and, hence, causes a reduction in the amount of soil organisms and releases labile soil carbon. This reduction leads to a poor and low crop yield and output.

Different agricultural systems impact the soil ecology in several ways, and the result of this can either be favorable or adverse depending on whether it is the bacteria or fungal composition that is affected. For example, Ph-sensitive organisms are impacted when lime is introduced into the soil; introduction of fertilizers to boost crop yields also affects the fungal composition in the soil; and manures also upset the carbon-nitrogen balance and ratio in the soil. Tilling also impacts the soil as it reduces fungal hyphens as the soil aggregates are broken down during tilling; tilling also affects the soil carbon and nitrogen levels. The aftermath effect of various agricultural practices on the soil ecology may be immediate or have long-term

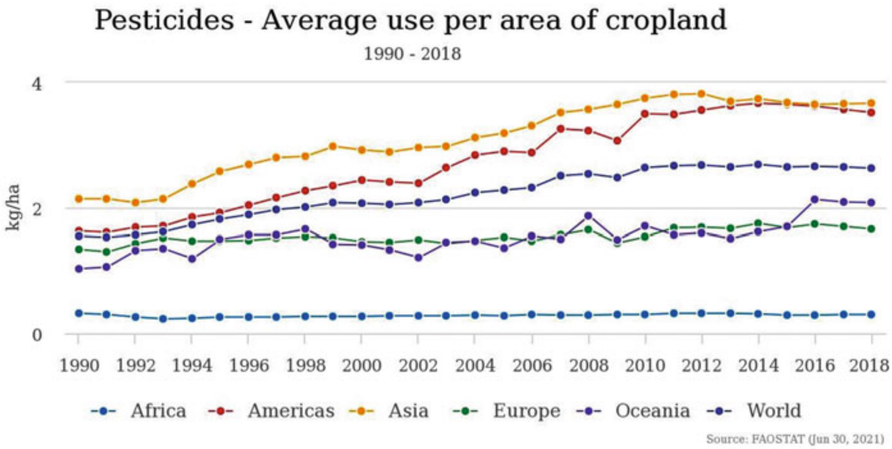

Fig. 3 Pesticide average use per area of cropland

impacts. Potential beneficial organisms that might be affected as a result of agricultural practices include those organisms that ensure fixation of nitrogen in the soil; organisms that are responsible for inorganic conversions of that ensure the availability of sulfates, nitrates, and phosphates for use to plants and organisms that ensure the decomposition and breakdown of organic matter.

Agricultural activities often require a lot of external inputs, which include pesticides, inorganic fertilizers to boost the productivity of the soil and ultimately increase crop yield and output. The farming systems that have incorporated the use of pesticides, inorganic fertilizers, and other external inputs to boost output and productivity have resulted in remarkable increase in overall food/crop yields. Nonetheless, the continuity of these practices has led to severe environmental degradation. This is especially true for soil, vegetation, and water availability. The level of soil organic has been on steady decline since the intense use of chemicals in farming systems (Singh and Ghoshal 2011) (Fig. 3).

Tillage

Tillage which is the mechanical manipulation of soil for the purpose of agricultural and crop production inevitably results in change of the properties of the soil such as infiltration and evapotranspiration processes, water retention capacity, etc. Even though the purpose of tillage is to increase or produce yields, it has adverse effects on the environment. As concerted efforts are made to meet the nutritional and food demands of the geometrically rising population of the world, it is important to ensure that soil is used in sustainable ways and that it serves as a carbon sink rather than a source of harmful sources to the atmosphere enhancing the impact of climate change. Due to the need to reduce land and soil degradation while still meeting increased demands for food, improved and more environment-friendly systems such as conservation tillage, cover cropping, mixed cropping, etc. (Corsi et al. 2012) have emerged as sustainable alternatives to the usual practice (Fig. 4).

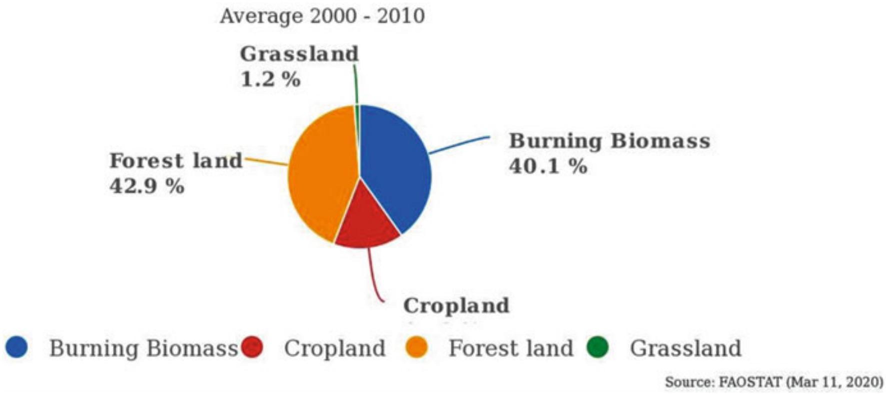

Fig. 4 Showing emissions/removals by land use

What Is Conservation Tillage?

Conservation tillage is a system where agroecosystems are optimally utilized to achieve food security and enhance productivity while at the same time preserving and improving the environment and natural resource base. Conservation tillage has as its characteristics the minimum physical and mechanical disturbance of the soil, mixed cropping, and constant soil organic cover. The Conservation Information Technology Centre (2004) also held that conservation tillage is any crop production method which ensures that nothing less than one-third of the surface of the farmland is covered with harvest which remains to lower the rate of the washing away of the topsoil. Conservation tillage (CA) is also explained as the process of mulching for land preparation before planting increasing the coarseness of the topsoil (Lal 1990).

The benefits of CA to the soil are many; some of the effects of CA on the soil are that it may likely increase the soil-organic carbon sequestering, improve overall soil structure, reduce incidences of erosion, and ultimately improve the environment. Crop residues are vital renewable resources, but how they are handled and managed can determine if they will have a positive or adverse effect on the soil and the environment at large. Systems such as uprooting and removing crop residues, burning residues, and even ploughing under residues can lead to reduced soil fertility and increased rates of erosion.

Types of Conservation Tillage

There are several types of conservation tillage:

- **No Tillage**: No tillage is a system of land management where the only disturbance done to the soil cover is that which is done during seed planting. This tillage system or approach is such that minimal disturbance which is allowed does

not affect the topsoil. It involves letting the crop residues cover the topsoil and mulch to boost the productivity of the soil.
- **Reduced Tillage**: Reduced tillage involves the use of primary tillage equipment like ploughs to till the soil.
- **Mulch Tillage**: Mulch tillage involves a system whereby crop residues are allowed to cover larger portion of the land assigned for crop production.

Effects of Conservation Tillage on Soil

There are many benefits of conservation tillage practices on the soil. Some of these include the following:

- Conservation and no-tillage system: The percolation of water is vastly improved as a result of no tillage; there are very few large pores. Water retention is boosted (Benjamin 1993). A conservation or no-tillage system improves the soil organic matter content. The population and activities of earthworms whose activities (burrowing) are vital to soil aeration and water percolation are significantly increased in a no-tillage system. Tillage practices affect the population of earthworms (Rasmussen 1999), and this was further corroborated by a 6-year study that revealed a major increase in earthworm population and activities as no-tillage system was adopted (Anderson 1987).

Effects of Conservation Tillage on the Environment

Conservation tillage holds many significant impacts on the environment. On the soil environment, conservation tillage leads to:

- Reduced runoffs into waterbodies from agricultural lands which carry agrochemicals that are harmful to the soil environment and reduce pollution of underground water (Duiker and Myers 2005)
- Reduced radioactive emissions from soil to the atmosphere, as tillage agriculture alongside other agricultural practices accounts for 10–12% of global greenhouse gas emissions
- Increased and significant carbon sequestration (Tebrügge and Epperlein 2011)

Effects of Intense Use of External Inputs in Food Crop Production

- Pollution of water bodies and soil from excessive use of fertilizers and animal wastes
- Increased cases of sickness and health challenges as a result of reckless use of pesticides and inorganic fertilizers
- Reduction in quality of soil and crop yield/output

- Salinization of soil and reduction in water sources and quality as a result of poor irrigation practices
- Upset in biological processes and physiochemical properties of soil as a result of intense tillage and burning
- Loss of biodiversity to the monotony in choice of crops grown for commercial purposes

Sustainable Livestock Management and Food Security

When it comes to the issue of climate change, we seldom look at farmers as major players and contributors. Nonetheless, farming activities (including livestock farming) have turned out to be key players and major contributors of greenhouse gases into the atmosphere. Activities such as farm product transport, fertilizer usage, land clearing, and animal husbandry are major sources of greenhouse gases to the atmosphere (FAO 2006). As much as farmers are significant contributors to climate change, they are also one of the biggest victims of the impact of climate change.

To meet the protein dietary requirement in our meals, we need increased livestock production. While it is known that ruminants contribute a lot to greenhouse gases (GHGs) in the atmosphere when they burp (Ripple et al. 2014), it is also known that the amount of greenhouse gases released into the atmosphere might be dependent on the type of feeds fed to the animals (Waghorn and Hegarty 2011). Can plant-based sources of protein be the solution as substitutes to animal-based protein, or do we take suggestions of improving livestock production through land management (FAO 2009; IPCC 2007)? In rain-fed systems being practiced in developing countries, it becomes a challenge to raise livestock as their food availability has come into question with climate bringing prolonged drought periods and reduced precipitations. This has led to long-distance migration of pastoral farmers and, in places like Nigeria, has led to severe conflict between herdsmen and crop farmers (Bello 2013) due to the competition for scarce resources. In developing countries, where most agricultural practices are climate dependent, a minor change in the climate patterns can spell doom for the whole nation and lead to severe food security problems. There is the search by governments, scientists, and farmers for a sustainable solution where we can mitigate the effects of climate change and at the same time sustainably engage in livestock production (Fig. 5).

Livestock Production, Environmental Sustainability, and Climate Change

Livestock farming is a significant contributor to the global greenhouse gas emissions (Gerber et al. 2013). The huge concentration of livestock in specific regions might lead to environmental challenges. The density of ruminants in the area can lead to increased levels of ammonia gas in the atmosphere and destabilize the land area's

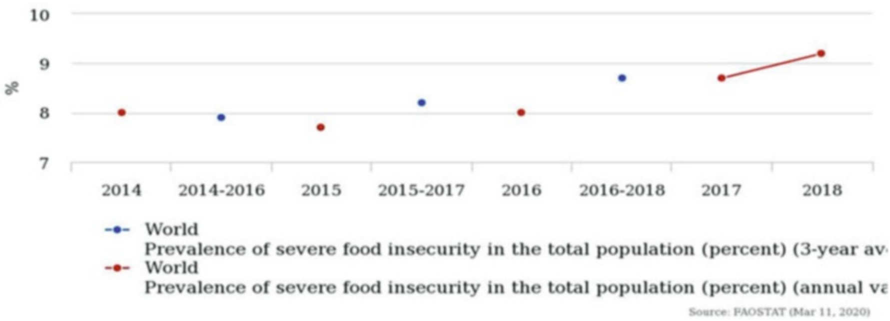

Fig. 5 Showing prevalence of severe food insecurity in the total global population (per cent) 2014–2018

nutrient equilibrium (Vitousek et al. 2009; Leinonen et al. 2018). Progress in achieving sustainable livestock production might lead to a significant potential to mitigating the impacts of climate change and global warming while improving the general state of the environment (Pelletier 2018). In recent times, significant reductions in the amount of greenhouse gases emissions per product have been achieved in animal production, for example, manure management, breeding, nutrient feeding optimization, and controlled breeding (Tallentire et al. 2018).

Livestock, Climate Change, and CO_2 Emission

Livestock production and grazing are a major source of concern when it comes to climate change because of the quantity of emission these ruminants release into the atmosphere leading to climate change. Ruminants release more greenhouse gases than pigs, chicken, and poultry, with the world estimation put at 2495 million tons of carbon. Ruminants produce methane as a by-product of digestion activity.

Methane is a greenhouse gas like CO2, but the adverse impact of methane on climate is 25 times stronger than that of carbon dioxide (Howarth et al. 2011). Out of all organic gases in the atmosphere, methane is the most available, and this gas in the atmosphere has risen at about 12 ppb/year in the past 10 years (IPCC 1995). Due to methane's radioactive forcing characteristics, it affects the hydroxyl radicals and carbon-monoxide concentrations and ozone chemistry (Raynaud et al. 1988). There are two ways in which ruminants release methane into the atmosphere: enteric fermentation and manure with enteric fermentation which contributes to climate change. The frequency of cattle grazing should be controlled to increase carbon sequestration in the soil. Noteworthy is the fact that methane emission, grazing frequency, and growth of vegetation cover are all connected. Carbon sequestration should be taken into consideration alongside greenhouse gas emissions whenever the role of livestock contributions to climate change is analyzed. Although the soil of grasslands has great ability to store carbon, recent studies have shown that high-grazing intensity has led to carbon escaping back into the atmosphere from grasslands where they were sequestered, and thereby, these grasslands become sources of harmful greenhouse gas emissions that contribute to climate change rather than carbon sinks (Janzen 2006; Ciais et al. 2010). More research needs to be done to derive feed and supplement that digest easily and release less methane as by-product from ruminants. Also, grazing areas should be clearly marked out and well coordinated and controlled especially in developing countries to ensure carbon sequestration through rotation of grazing.

Ways to Achieve Sustainable Livestock Production

More than ever, there is a global cry for improved and efficient food production system. It is on record that out of every seven persons, one of them is undernourished (FAO 2009). Climate change and unpredictable weather coupled with rapidly increasing global population, urbanization, and land degradation have drastically reduced agricultural output. In the past 10 years, in one-quarter of world countries, the cereal outputs have reduced per hectare while there is a skyrocketing demand for animal protein by the geometrically increasing global population. The rate at which humans consume animal protein is altogether considered not sustainable and is inversely proportional to the capacity of earth to meet the dietary requirement of its people. Annually, over a billion tons of crops such as oats, millet, and wheat used in feeding animals or preparing animal feeds could alternatively meet the food needs of over 3.5 billion human beings. Nonetheless, this reasoning perspective does not take into consideration the associated numerous health benefits of consuming required amounts of animal protein and that these animals can eat foods that man cannot consume.

Livestock farming and crop cultivation/farming go hand in hand complimenting each other (Herrero et al. 2020). Over half of the food consumed globally emanates from farms engaged in both crop and livestock farming. Their interdependence and relationship can be seen in practices such as animal manure used to fertilize the soil for optimal output, ploughs pulled by animals, and the postharvest residue which provides food for the animals. Despite these, the increased demands for milk and meat from animals can upset this existing equilibrium. As a result of the demand for animal protein by the global population, livestock farming has intensified without regard for sustainability and overall efficiency (the net amount of food produced in terms of inputs such as land and water). There is no plan in future to expunge animal protein from human diet; hence, it is time for all stakeholders to embrace sustainable livestock farming ensuring that best practices are maintained, and the planet is safe.

Virtually all the meat and milk consumed globally is obtained from ruminant sources (goats, cows, sheep, etc.). Below are methods and plans to engage pragmatic sustainable livestock farming systems. These methods and systems highlighted below will provide environmental and economic benefits while increasing quality and quantity of outputs.

Maintain Animal Health

The popular saying goes "You are what you eat," so can eating sick animals make people sick. It is on record that 13 related zoonotic diseases (diseases that affect both man and animals) cause 2.4 billion cases of illnesses, and 2.2 billion deaths yearly in developing countries are zoonotic (Grace et al. 2012). Regardless of this evidence, human and animal sicknesses and diseases are still treated as different problems. Livestock management systems should include ways and methods to manage communicable/zoonotic diseases through measures such as better hygiene, quarantining new arrivals on farms, and putting in place a systematic supervised, sustained monitoring for diseases that cross species or countries' borders. Poor management of livestock makes them easily vulnerable to infections and diseases. A lot of animals die before attaining table size or becoming able to produce milk. This lowers output, adversely impacts the environment, and reduces the farmer's ability to choose the best performing breed for production. The government can step in the area of providing aid to small livestock farmers and raise awareness on the issues of sustainability and climate change as this will improve overall livestock farming and more animals will survive to table size, hence better quantity and quality.

The practice of keeping many animals clustered in a small space accelerates the spread of infections and diseases. Globally, around 5 billion USD is lost annually to foot-mouth virus vaccination. The foot-and-mouth breakout in the United Kingdom in year 2001 led to the annihilation of about six million farm animals. The impact of these losses is felt across all industries and sectors of the global economy. There is a shift and growing awareness on antibiotic resistance in animals and the need to address diseases and inspection spread through implementing better and sustainable management systems (such as reducing overcrowding) and practices rather than relying solely on anti-infective drugs. Focus is shifting to treating individual sick or infected animals rather than the whole herd, and evidence of this working within the local settings will make it easier for farmers in such areas to adopt modern and sustainable practices.

Use Supplements

Research should be carried out to identify microbes of nutritional benefits to livestock and affordable ways to adopt them. This should be supported by the government through policies and aids. Productivity and performance of livestock can be considerably increased by using supplements. For instance, some supplements boost the growth of microbes in the rumen of ruminant animals which improves nutritional value derived from feed consumed. Certain extracts from plant can change the microbial population in the rumen of a ruminant animal improving nitrogen and energy efficiency. The implication of this is significant increase in milk and meat production and a significant proportional decrease in by-product greenhouse gas. In Australia, there is a deep-rooted plant known as tar bush, and livestock in the region feed on it. This plant fights gastrointestinal nematodes, acidosis, and also reduces methane emission in the environment.

Consuming Less Quantity and More Quality

The consumers have a role to play in the shift toward sustainable livestock production. The demand always determines supply; if the end consumers will demand for quality and not quantity, livestock producers will be forced to focus more on the quality of the milk and meat produced. The quality of meat and milk produced has a direct significant impact on the health of the consumers. The focus should be on eating less and eating quality. In developed countries, the high quantity and low quality of animal processed foods is partly responsible for ill health in the society. Some of the resultant illnesses related to consumption of high quantity but low quality of meat include cancer and coronary heart disease. However, for the people who live on less than a dollar a day, there are obvious nutritional benefits to consuming little amounts of quality meat. These advantages and benefits include essential amino acids, iron, and various essential micronutrients that increase chances for proper physical and cognitive growth (Smith et al. 2013). The public-health goal, therefore, should be to balance nutrition across the globe.

Give Less Human Food to Animals

Ruminants graze on pastures and can consume hay and high-fiber crops that are not palatable for humans to feed on; nonetheless, animals consume one-third of global cereal production, and 40% of that goes to cattle. Unlike poultry and pigs, ruminants have a four-set stomach which has the biggest compartment known as rumen that houses microbes that break down high-fiber plant food into calories and top-quality protein. With these stomachs, ruminants can adapt to and survive grazing mountain sides and lowlands and let agricultural lands be used for crop production and crop yields be consumed by the billion undernourished people around the globe. For example, in New Zealand, the dairy industry sources over 90% of nutrition by grazing their livestock on pastures (Bocquier and Gonzalez-Garcia 2010).

Harmonize Farming Practices with Local Culture

A major percentage of the global poor rely solely on agriculture as their mainstay. Agriculture for them goes beyond a means of survival and feeding; in most cases, it is a vital part of their culture. Livestock production especially contributes great benefits for the people beyond just farming (Otte et al. 2012). In many developing countries, families raise livestock, and when major expenditures arise such as weddings and medical treatment, they sell some of their livestock to meet these needs. This local system of grazing and mixed farming is changed when there is interference of commercial and modern systems that aim to maximize output and profit in the short term.

Raise Native Species

The quest and unbridled drive for financial gains and high productivity have made a lot of livestock farmers adopt adverse schemes of importing foreign species which often cannot adapt to the local environment because of their genetic makeup. A good example of this case is that of the Holstein cow breed introduced to Africa.

Governments, charities, and nongovernmental bodies in the bid to address poverty and improve the livelihood of the people introduced the Holstein which is known for high milk production. The genetic makeup of the Holstein does not have embedded hardiness, disease resistance, parasite resistance, and heat resistance. These were not taken into consideration before introducing this foreign specie. So, livestock farmers that own the Holstein breed cannot graze their cattle on pastures for fear of disease and pests such as a tick and end up keeping their animals in stalls having to bring their feed to them and in some cases go through the rigorous and super expensive process of importing their feed. Despite this unsustainable practice and high cost of animal welfare, the animal only produces one-third of the quantity produced when they are in the temperate regions. For the local livestock farmer, it is better to own smaller and local cattle than larger cows that are too expensive to keep alive. Native cattle in humid regions of West-Africa have over thousands of years of exposure to the trypanosomiasis from the tsetse fly and have developed resistance to the disease. In the quest for bigger profits, farmers replace their local species with European and North-African species like the Zebu cattle which have no resistance to trypanosomiasis. This makes the livestock to spend a fortune on drugs to keep cattle healthy because of the prevalence of the disease in the region. Farmers need to be encouraged to embrace their local species that are adapted to the climate and resistant to local diseases.

Agroforestry

With increasing rate of climate change and modern focus on sustainable agricultural production, agroforestry, we remain associated with sustainable livestock production. Integrating agroforestry with animal agriculture has the potential to limit many challenges associated with livestock production. Due to changing climate, and associated with heat stress, agroforestry can prove a source of shade in grazing animals or even among sedentary animal to serve as a source of shade. Due to the ability of trees to use carbon and provide oxygen, agroforestry can be a good source of carbon and nitrogen mining (Spore 2016a, Song et al. 2020) to provide cleaner environment for livestock which is part of ecosystem services. This integration can come in the form of silvopastoral system. Integrated land use practices, such as agrosilvopastoral systems, combine high C stocks with high C sequestration potentials (Mbow et al. 2013). This practice of silvopastoral system is widely accepted in South American countries such as Colombia, Argentina, Peru, etc. This system is well known to improve soil nutrient quality, environmental service, and sequester carbon (Mosquera et al. 2012; Congio et al. 2021). Agroforestry could be a win-win solution to increase the storage of carbon and may also enhance agricultural productivity. Furthermore, agroforestry members such as *leguminous* spp., *Leucaena* spp., *Enterolobium* spp., and *Gliricidia* spp. have nitrogen-fixing ability. Agroforestry trees can function many forms such as fodder for animals due to the high protein content in their leaves; they can fix atmospheric nitrogen which helps to improve soil fertility. Further, the seed or leaves or stem of some trees such as neem, *Salix babylonica*, *Kochia indica*, and cascalote fruit (*Caesalpinia coriaria* J. Wild.)

(Elghandour et al. 2017; Jack et al. 2020; Manuel-Pablo et al. 2020; Jesu's-Martı'nez et al. 2020; El-Adawy et al. 2020) has been reported to serve as an alternative source of protein, growth promoter, and use in ethnoveterinary medicine, and reduce greenhouse gas emission of livestock.

Climate-Smart Farming

Climate-Smart Livestock Farming Through Livestock Feeding and Forages

Climate-smart livestock farming can play a huge role in sustainable livestock production. This climate smartness comes from improved livestock feeding and forages. They can be suitable for adaptation and mitigation in the face of changing climate (Njarui et al. 2020). Typically, in the tropical regions, poor feeding and husbandry result in lower milk production and growth which causes higher emission intensity. However, manure management, pasture improvement, and silvopastoral farming will play an important role to improve productivity band and reduce emissions (Paul et al. 2020a). Forage is important in smallholder farming systems because it links soil, crop, and livestock component. Thus, changing livestock feeding can have a multidimensional impact on productivity and environmental quality (Paul et al. 2020b). The use of *Brachiaria* spp., as a climate-smart grass, promises high amount of palatable, nutritious biomass for livestock, which can grow on infertile soil, sequester carbon in soil (Njarui et al. 2020). In addition, the organic carbon in *Brachiaria* fields will improve soil-organic matter content, which will in turn enhance soil fertility and hence improve productivity.

In the same vein, smart use of agro-biodiversity in the climate-smart agriculture can provide additional benefit of biomass and soil fertility to farmers, through the combination of grasses and legumes. The benefit of growing legume-based cropping system and *Brachiaria* grass forage includes improved milk production and composition (Tesfai et al. 2019). Muinga et al. (2016) showed that feeding *Brachiaria* grass in combination with Napier grass and maize stover improved milk yield by 15–40%. Similarly, Ngita et al. (2016) reported that *Brachiaria* grass improved average daily gain and consequently total weight gain in goat compared to those fed with Rhode grass. In addition, integration of Cayman grass and leguminous shrubs (*Leucenea* spp.) improved weight gain, and the emission generated on the legume-based system was low (Gaviria-uribe et al. 2020). This suggests that they are a good option in achieving lower emission in pasture-based ruminant production system. Novel processing methods such as pelleting of forage legumes showed little effect on pellet nutrition but reduced the fiber fraction (Oyeniran et al. 2018). This suggests that the technique could be deployed in grasses and could be employed during wet season when there is high-forage regeneration especially in areas with customary on and off growth rate in rainy and dry season.

Implementation of Efficient, Eco-Friendly, and Adaptive Animal

The type of animal deployed for production could be a climate-smart move. It is reported that cows have high dairy productivity than small ruminants while small ruminants have high fecundity, greater prolificacy, shorter reproductive cycle, and short cycle for meat production (Sejian et al. 2021). Furthermore, small ruminants have higher dairy production carbon footprint while meat production of beef cattle has higher carbon footprint (Phiri et al. 2020; Adegbeye et al. 2020b). Therefore, raising small ruminants for meat while large ruminants for milk could be a climate-smart move. In the face of changing climate and water scarcity, it is important to raise livestock species that can adapt. Carmel may play and important role as well as small ruminants in adapting to climate change and water scarcity. Small ruminants can tolerate up to 33% water-restriction level without compromising production (Adeniji et al. 2020). Furthermore, in arid zone, where water scarcity is higher, inclusion of cactus pear silage up to 42% in goat diet during periods of water shortage improved eating, rumen efficiency rate, and water retention. This suggests that in the period of water scarcity now and in the future, cactus pear can be used as silage material in regions experiencing water scarcity in order to combat the issue of dehydration in ruminant livestock.

Sustainable Crop Production

By 2050, the global population is estimated to be about 9.1 billion persons. All human beings survive on food, and there is increasing pressures on natural resources man depends on for survival as a result of the geometrically increasing global population. There is not only an urgent need to increase and intensify crop production but also the need to do so in a sustainable manner. The key issue here is to get farmers to adopt sustainable practices and ensure that knowledge on sustainable best practice is continually shared among farmers and innovation is continuous. To meet food demands (human consumption only) in the next 40 years, crop production will have to go up by 70% in developed nations and a hundred percent in developing nations. In comparison to production between the years 2005 and 2007, this increase in food production will mean an additional 1 billion tons of cereals, 200 million tons of meat to be produced yearly (Bruinsma 2009). In the past, cultivation of more lands and exploiting fisheries was a potent solution to the issues of food shortages, but now there is the severe issue of land fragmentation as a result of population explosion and need for urbanization. There is also shortage of other resources needed for agriculture such as water and energy. Climate Change has further worsened the issue of food security as farmers are not able to precisely predict the weather and therefore lose a lot of their produce due to cases of prolonged droughts and irregular precipitation (Godfray et al. 2010). It is increasingly difficult to make more lands available for crop farming as man will have to encroach into forest areas, and this will be a major setback in the climate change fight as the forests serve as carbon sink, and all the carbon held for hundreds of years will be lost and released back into the atmosphere, and there will be a major loss of biodiversity (Balmford et al. 2005).

In the bid to increase crop productivity to meet food demands, the focus now is to ensure resource efficiency per output. The challenges (land competition, water and energy efficiency, and climate change) affecting intensified food production are all intertwined, and therefore the potential solutions will be to:

- Support and boost innovation in agriculture.
- Foster national and international research collaborations.

Sustainable Crop Production Systems/Practices

Cultivars

To be able to produce and provide food enough to meet the demands of the skyrocketing population, farmers will need to adopt and use genetically upgraded varieties of crops that are usually disease resistant and climate change resistant. There is need to have crop varieties that can survive in both temperate and tropical regions of the world and resistant to pests and diseases. These crop varieties will need fertilizers and irrigation. Nonetheless, there have been issues with public acceptance of genetically modified crops. It has continually been debated in various circles, and people are skeptical about it. Even with the introduction of scrutinizing science-based risk investigation, this debate has turned highly politicized and factionalized in some countries, especially in Europe. Our opinion remains that genetic modification is a viable and valuable method with benefits and disadvantages which must constantly be weighed rigorously on an evidential, inclusive, case-by-case ground.

Organic Agriculture

This is a farming system which does not involve the use of chemical fertilizers, pesticides, and other chemicals. Foods produced organically are very healthy and have no adverse effect on the final consumers. In recent times, people have started to shift from foods that were grown or produced with the use of chemicals, and there have been links with these foods causing several diseases including cancer. Organic farming will only be sustainable if practiced alongside conservation agriculture with very little tillage or zero tillage where the soil is barely disturbed and recuperates naturally. Practicing organic farming with the usual tillage system will most times stress the soil, because it will be turned several times, and this will ultimately affect the output and yield making it very inadequate in meeting the demands of the growing population. Organic farming in combination with conservation agriculture will lead to increased nutrients, soil organic matter, improved soil health, and productivity.

Conservation Agriculture

Conservation agriculture refers to an agricultural system of crop production that involves resource efficiency and environmental sustainability. It is practiced to attain sustained high output levels not using up the fertility of the soil while at the same time preserving the environment and bringing in profit. Tillage practices are next to nonexistent or at lowest levels in conservation agricultural practice. In this system, organic fertilizers and not those of chemical origins are adopted to maintain optimal production levels and not upset the natural and normal biological processes. The foundation for conservation agriculture is healthy soils with three underlining principles:

- Minimum or zero tillage/direct seeding
- Cover cropping and soil cover with crop residue
- Crop rotation

Conservation agriculture allows for good agronomy practices which include improved land use and land management for rain-fed and irrigated farming, timely planting, and this improves the overall productivity of the soil. This system is complimented by integrated pest and weed management and use of viable seeds. Conservation agriculture has so many benefits, and some of them include improved water retention and water percolation, improved soil moisture, energy efficiency, improved soil organic matter, better structure of soil, reduced incidences and cases of soil wind and water erosion, less capital intensity, reduced labor, improved carbon sinking, and improved soil biodiversity (Cook 2006; Huggins and Reganold 2008; Stagnari et al. 2009; Kassam et al. 2012). Furthermore, there are reduced levels of erosion, with the lands being restoration/regenerated and more lands reclaimed, and productivity boosted to better levels before they were exposed to intensive tillage practices (Montgomery 2007; FAO 2011). Conservation agriculture is known to lead to significant produce output and yield between a 40% and a 100% increase above the usual/normal levels where it is being practiced. In farms where conservation agriculture is practiced, there is reduced use of power and energy, reduced use of fertilizers and other agrochemicals, and reduced time and labor input.

Despite the many benefits of conservation agriculture, it has its own limitations. The limitations of conservation agriculture include likely increased crop diseases and pests, growth of weed species that are herbicide tolerant, and excessive soil moisture content.

Weed Management and Control

Weeds compete with crops for essential nutrients that are needed for growth. If allowed, they ultimately lead to significant decrease in output and yield. Fashioning out a system to address weed growth without altering the quality of final output and without degrading the environment is a step in the right direction. Integrated weed control and management system involve having a good knowledge of crop-weed relationship in the bid to determine advantageous points to improve crop competition, growth, and survival. Some of the practices for weed management include crop rotation, adjusting planting time, mulching, adoption of cultivars, use of improved seeds and seedlings, etc. There is the need to constantly come up with innovative systems to manage weeds; therefore, more research in this line should be encouraged. Research in the area of diversified weed management methods is germane to achieving food security and ensuring the sustainability of the planet.

Nutrient and Fertilizer Management

With continuous and intense use of the soil for crop cultivation especially under a tillage system, the micro- and macronutrient levels begin to drop. Often, the lands are not allowed enough time to regenerate and fallow before they are used for crop production again. Healthy soils are needed to meet food production requirement to feed the geometrically increasing global population. Soil rich in organic matter is key to high productivity. There is need for the judicious use of mineral fertilizers in such a manner that it gets to the plants and not pollute the environment, soil, and surrounding water bodies. To also keep the soil productive, there is the need to adopt nitrogen-fixing trees and crops and use manure. The government needs to do more to support healthy soils by enacting policies that drive conservation agriculture, mixed farming, and agro-forestry. These policies should discourage mechanical tillage and unbridled use of chemical fertilizers but encourage site-specific nutrient management.

One of the first steps in nutrient management is testing the soil for available nutrients. A lot of farmers do not test for nutrient contents but just go ahead to use manure and fertilizers not being site specific. Soil testing will reveal what intervention and nutrient is suitable and needed to boost the productivity of the soil. Nevertheless, soil testing is not always accurate, and thus, there is the need to improve soil testing to predict better the nitrogen supply in the soil. One of the ways to reduce soil nutrient loss is to adopt conservation tillage where mechanized tillage is reduced to the barest minimum. Integrated crop-livestock system created room for a close-circuit recycling on nutrient (Adegbeye et al. 2020a). Through integrated crop livestock system, sustainable agriculture is possible. Some successful sustainable management of manure is practiced in an orchard in Iran (GIAHS, 2011). In this cases study, due to the soil quality in Iran, the soil around the root of each plant is excavated and replaced with organic manure that has been composted. This manure proves a means of nutrient to the plant or tree. To improve the organic manure quality, vermicomposting, co-composting of manure with other organic matter could be useful (Adegbeye et al. 2020b). Similarly, biocharring of wastes could be a useful way to manage manure in a sustainable way to return valuable nutrients to the agronomic and agroforestry system (Adegbeye et al. 2020a, b). In this way, crop waste and animal manure are pyrolyzed to stabilize and harness the nutrient in manure, and this manure can improve yield, tree survival, soil structure, and microbial community (Wang et al. 2019, Lefebvre et al. 2019).

Water Management

In agriculture, water is required for plant growth and survival; it is essential to achieving sustainable agriculture and improved productivity. Climate change has made rain-fed agriculture very unstable, and this had led to a lot of farmers losing all yields and their livelihoods. The unpredictability of the weather has forced some farmers to look to other places for their livelihoods. Climate change has led to prolonged periods of drought, and this causes the ground to cake and have a hard pan on the surface making water percolation near impossible. To achieve high productivity and sustainability, there is need to investigate ways of making water available for crop production all year long. To help maintain soil water, practices such as mulching and minimum or zero tillage will help achieve this. Also, there is need for more research to obtain improved seeds that can cope with extended drought periods. Irrigation is a way out, but it has remained economically unattainable by small farmers, and therefore, the government needs to step in to assist farmers in irrigating their lands with modern systems that are precise and ensure efficient use of water supplied. Water harvesting is also a water management technique especially in regions that depend on rain-fed agriculture. To ensure all year round farming, harvesting rainwater in large tanks or dam during rainy season and combining such technique with drip irrigation prove to be a measure of sustainable agriculture. For farmers who have access to unclean waters, such water can be used to irrigate inedible but esthetic plants such as lawn and horticultural plants.

Precision Agriculture

In conventional farming systems, inputs are applied on presumptuous grounds, but precision agriculture holds that even within a field, management practice allows for specific management of soil, pests, and water according to their localized difference within a particular area. Precision agriculture allows for efficient use of resources while achieving optimum output and environmental sustainability. For instance, rather than the application of nitrogen fertilizer for the purpose of yield and maximum output, precision agricultural pushes for soil testing to determine the exact amount needed to improve the soil productivity. Precision agriculture is very broad and covers so many areas such as water management, weed control, pest management, nutrient management, etc.

Soilless Farming or Hydroponics

As human population has skyrocketed so is the demand for food while available land for agriculture has diminished rapidly. The constant increase in the standard of living across the world has led to increased demand for high-value crops. These demands are even high during off-seasons. In the bid to meet these demands, researchers have come up with the soilless or hydroponic farming method. Some of the driving forces behind the development of soilless farming include rapid growth and multiplication of soil-borne pathogens in intensively cultivated greenhouses and easier control over crucial factor that determine the success or productivity rate of crop. Plants raised in soils are exposed to a lot of water right after irrigation. At this point, the macropores of the plant get filled with the water, then followed by a gradual removal of the water and infilling of the soil macropores with air (oxygen). The oxygen in the macropore is used up quickly by soil microflora and taken up by plant root at a rate faster than it can be replenished. When evapo-transpiration takes place and the moisture and water content is drained, the soil becomes so porous that oxygen from the atmosphere diffuses easily into the plant roots. At this point, a little water is held by slowly increasing soil-matric forces so that the plant can invest a significant amount of energy to absorb enough water to make up for water lost through transpiration due to atmospheric demand. Over time, it is now known that plants grown in porous media or near container capacity need less energy to take up water.

Soilless farming allows for control of nutrient availability to crops/plants than in conventional farming systems. Easy and rapid spread of diseases through soils after repeated use, inadequacy of healthy soils, has led to more people adopting the soilless farming system. There is a negative side to soilless farming, that is, in soilless farming, the root system of plants is restricted to the containers where they are grown whereas in conventional soil farming, the roots can grow as much as possible to find the required nutrients and water for the plant. The limited root system means limited nutrient supply (Dubik et al. 1990). Soilless farming using the container system has an edge over the conventional soil farming system in that it restricts environmental, soil, and water pollution as the container restricts the leaching and washing away of pesticide and other chemicals thereby protecting the water bodies. Soilless farming also has the advantage of water efficiency and nutrient-use efficiency which ultimately leads to increase yields and output during harvest. In the western world, soilless farming is gaining more attention because of climate change and the sustainable development goals. Soilless farming allows for upcycling and recycling of plastics rather than have them pollute the environment, pollute the oceans, and contribute greenhouse gases into the atmosphere. Regulations are now being put in place to ensure adherence to recirculation to reduce and possibly eliminate harmful chemical runoff from plant nurseries and greenhouses. Easy and cheap soilless farming system has grown to become part of the solution to meet the increasing demand of the growing global population which in time past has been a difficulty because of lack of fertile and healthy soils and technical know-how. Knowing that the food needed to feed many people can be sourced from a small, cultivated area has drawn so much attention to soilless farming. Nonetheless, there is the need to find cheaper and durable alternatives to the pricy equipment used for soilless farming for rural farmers. An important advantage, and highlight, of soilless farming is the efficient water management making crop production possible in areas of low water quality and water scarcity.

Incorporation of Renewable Energy into Farming

Solar into Rural Area

Sometimes, sustainable agricultural practices might not be in the form of creating a complex technique, it could simply mean finding a new way to make use of resources that can never be exhausted. The tropical area in the world is often characterized by high temperature that comes from sun impact. One of the challenges faced by food production system in developing countries especially the rural areas is food waste and poor energy supply. These two challenges are somewhat related. Tapping the solar powers in rural areas can provide energy and improve storage. Since solar power is a clean energy, it could be a source of sustainable agriculture if harnessed. Solar power can supply energy to rural communities both during farming season and harvest to reduce postharvest loss. One of the ways to reduce losses is through solar drying of fruit and vegetable to improve their shelf life (Spores 2016b). Not only will it improve shelf life, but also improve food hygiene. Sun drying on sacks, pavements, and in the open gives room for insect and dust to contaminate harvest. The use of solar power as a source of food drying is already being practiced in kiburi food processor, Kenya, which uses solar power to dry mangoes (Spores 2016b). Furthermore, as a source of energy, solar power is used for lightening, and refrigeration and subsistence farmers use solar-powered water kit to pump water into tanks which are used for drip irrigation to irrigate horticultural crops.

Anaerobic Digestion

Anaerobic digestion is the process of fermenting organic material in anaerobic environment in the presence of microbes with the aim of producing organic energy. The manure from animal is used as feed stock for anaerobic digestion to produce methane gas. It is reported that proper manure management can reduce methane emission by up to 90% (US EPA 2013). Adoption of this anaerobic digester either as surface biodigester, or as submerged or portable biodigester by small-scale farms, can go a long way in improving sustainable agriculture with regard to livestock, environmental stewardship, and bioenergy supply. Biogas is already being adopted in Songhai farms in Benin Republic and in other developing and transitional nations such as Nigeria, Vietnam, Ethiopia, India, and China. Therefore, widespread adoption in rural areas could go a long way in enhancing renewable energy for sustainable agriculture.

Integrated Watershed Management

Rain-dependent agriculture is responsible for 58% of the total global food production (Raju et al. 2008), and as a result of the constantly increasing global population, water as an essential resource for crop cultivation is becoming increasingly scarce. The scarcity is worsened by climate change (Molden 2007). Integrated watershed management produces multiple socio-political-ecological benefits; the management of natural resources at watershed scale leads to improved standard of living as a result of improved livelihoods, increased food production, environmental preservation and improvement, and empowering marginalized women in the society (Sharma 2002). A watershed can also be referred to as a drainage basin/catchment area, and it is an area where all incoming flowing water goes to a unified outlet. Livestock and the people are key parts of the watershed and determine the level of utility and productive of the watershed. The integrated watershed system involves the amelioration of production technologies within the natural water catchment area for optimal output and development of land, water, and crop resources to meet the basic needs of the surrounding dwellers and animals in an environment-friendly (sustainable) manner. The approach entails mixed cropping, integrated nutrient management, integrated pest management, land and water conservation, etc.

Adaptation in Agriculture to Climate Change to Address Vulnerability

Agriculture as we know in most parts of the world is still climate and weather dependent making the practice so vulnerable to any slight changes in the usual order of things (weather and climate). The vulnerability of agriculture to climatic and weather changes leads to several adverse outcomes such as reduced outputs, susceptibility to diseases, increased pest attacks, etc.

Over the years, farmers and affected stakeholders have sought and enacted systems to adapt to the impacts of climate change (Smith 1993). In adopting an adaptation measure or system, it is important to note the key characteristics that should be present in such adaptation system/measure (Smithers and Smit 1997). These adaptability characteristics are explained below:

- Intent and Resolute: This helps to differentiate between adaptation interventions that are spontaneous and those that are carefully conceived with climate risk as the foundation of the intervention measure (Bryant et al. 2000). Adaptation measures are supposed to be designed within specific socio-economic-environmental conditions. To ensure adaptation measure selected is sustainable and not only spontaneous, but also evidence based and properly planned.
- Duration: The system of adaptation to be adopted is either proactive, concurrent, or reactive. While understandable in theory, in practice, this dichotomy is difficult to differentiate. Duration in adaptation highlights responses in terms of the duration of time in which they are applicable; short term versus long term (Stakhiv 1993). Short-term adaptation measures (within season) in agriculture may include getting a bank loan, sale of livestock, etc. while long-term adaptation measures will include things such as long-term insurance and land use change, etc.

Types of Adaptation

There are several types of agricultural adaptation to the effects of climate change. This section gives several examples of such. The examples highlighted below were sourced from real-life farmers group and concerned government agencies (Wall 2001). Adaptation refers to the socio-economic-ecological adjustments enacted in response to climate change.

Agricultural adaptations are categorized into four separate categories which are not mutually exclusive. These groups are the following:

- Government programs and agricultural insurance
- Farm production practices
- Technological advancements
- Farm financial management

Technological Advancements

(i) Crop Development: This adaptation system involves the development of new crop varieties including hybrids to enhance the tolerance levels of crops to weather and climatic changes.
(ii) Climate and Weather Information Systems: This adaptation is one that entails use of technology to predict daily weather and make seasonal forecast, helping farmers better prepare to address issues and concerns that affect crop production.
(iii) Innovations for Resource Management: This involves water management techniques which covers areas such as irrigation, with the sole aim of addressing low and fluctuating precipitation and moisture levels and drought periods. Adaptation here also addresses farm-level resource management that addresses factors such as temperature, soil organic matter content.

Farm Production Practices

(i) Farm Production: This involves crop rotation and crop substitution to address environmental change and relevant economic risks with climate change. This also involves diversifying livestock varieties to deal with anticipated risks such as environmental variations. This also helps to deal with spread of diseases. Farm production also requires adjustments to ensure adaptation to climate in rearranging production schedule to address economic risks associated with climate change.
(ii) Land Use: This involves crop and livestock rotation to adapt to the environmental changes caused as a result of climate change. This also involves the engagement of various tillage practices to ensure soil nutrient availability for crop production and also maintain soil moisture levels.
(iii) Land Topography: To address changes associated with climate change such as accelerated land degradation due to increased precipitation and erosion, it is pertinent that farmers need to grow crops that can hold the soil together to reduce run-offs and washing away of the top soil. Cover crops are good examples.
(iv) Irrigation: Climate change has led to the fluctuation of rainfall amount and intensity, and this has adversely affected crop and livestock production. For crop farmers to maintain production rates, they will have to embrace irrigation to continuously supply water to crops.

Government Programs and Agricultural Insurance

(i) Assistance Programs and Subsidies: Governments need to step in to assist farmers in providing them with modern and climate change adaptation farming technique and systems while also subsidizing agricultural inputs to help farmers manage risks associated with climate change.
(ii) Private Insurance: Develop private insurance to help farmers cope with risk that might arise due to climate change in terms of losses and infrastructure.
(iii) Resource Management: Governments need to develop policies that ensure for more resource efficiency, resource use, and management at farm level with regard to the changes brought about by climate change.

Farm Financial Management

Household Income Diversification: In the face of climate change, it is pertinent for households that solely rely on agriculture as their only source of livelihood and mainstay to begin to seek alternative sources of income to deal with the economic risks associated with climate change.

Solutions and Sustainable Practices That Encourage Natural Resource Management

Pasture Management

This process involves adopting strategies like rotational grazing through the introduction of paddocks and consciously introducing/adding nutrient-rich legumes to pasture lands. Through communal pooling of resources for value creation, a rotational approach can be adopted, and nutritious and healthy diets can be made available to livestock all year round despite fluctuating climatic conditions. Food Waste Management: The not so physically attractive portion of harvest that does not make it to the markets and stores instead of being wasted can be processed to feed livestock, if they are suitable for consumption as part of animal feed. Through this system, livestock feed on more nutritious components improving their well-being and output.

Stakeholder Management

For adequate resource management, all stakeholders must be made to realize that they play a very important role in ensuring that these resources are available for the next generation to meet its need too. It should not only be the duty of the government but also of all relevant stakeholders, especially the local community. This is very critical in ensuring sustainable practices and natural resource management. It will require a lot of training, sensitization, and partnerships.

Mixed Farming

Mixed farming should be encouraged to create a circular system in farming communities where nothing is a waste product. In a mixed farming system, the harvest crop residues that are usually left to rot can be processed to feed the livestock, and the livestock dung can be managed for manure to the soil.

Crop Rotation

Crop rotation reduces the need for harmful synthetic chemicals (herbicides and pesticides), increases biodiversity, improves structure of soil, and enhances the crop and farmers' resilience to harsh weather and climate conditions. The problems and challenges in natural resource management make it obvious there is no one single solution to achieving sustainable agriculture globally. There is a lot of work to be done on the part of the governments with regard to laws and policies that favor sustainable agricultural practices. Moreover, the land tenure system is another vital issue that needs to be investigated if we are going to efficiently manage our natural resources and practice sustainable agriculture.

Conclusions

Natural resource management and sustainable agricultural practices have a vital role to play in climate change mitigation and adaptation. In this chapter, farmers and government parastatal have an important role to play in the mitigation and adaptation. On the animal side, to mitigate and adapt to climate changes, farmers can engage in climate-smart livestock farming such as maintaining animal health, use of supplements, cultivating and feeding improved forages, use of Indigenous animal species, and silvopastoral farming. These techniques will improve the growth of livestock and improve rumen efficiency and animal well-being which will result in less GHG emission per kilogram of animal protein derived. The use of improved forages to feed ruminant will reduce the need for farmers to feed ruminant with human food, and this will result in more carbon sequestration and reduce the need for farmers to open more land for planting. In fact, some of these improved forages like *Brachiaria* plant have biological nitrogen inhibition which will reduce nitrous oxide emission. Engagement of silvopastoral farming also helps improve soil quality, carbon sequestration, create a microclimate which helps reduce ambient temperature, reduce wind speed, reduce greenhouse gas emissions, enhance soil fertility, and improve ruminant growth. On the crop side, farmers are encouraged to engage in sustainable practices such as the use of improved crop cultivars, organic and conservation agriculture, nutrient and fertilizer management, and incorporation of renewable energy into farming. These techniques are both climate change mitigating and adaptation. The use of improved crop cultivars means that these crops are resistant to pest and disease, and they grow quick with less need for water. Engagement in organic agriculture nutrient and fertilizer management, water management, and incorporation of renewable energy into farming is important too. These techniques will reduce the use of synthetics and improve the use of organic fertilizer which will enhance nutrient recycling in agriculture and reduce greenhouse gas emissions. Incorporation of renewable energy into farming reduces food waste because it can be used to preserve food, and food preservation reduces greenhouse gas emissions since excess food can be kept for a very long time, so the need for tillage will be reduced.

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