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Preface

Deterioration of land due to intensive agriculture is creating trouble for food security. Hence, appropriate measures should be taken to prevent land from being destroyed. This includes adoption of sustainable cropping systems under changing climate through the aid of process-based models. Land on planet earth is mainly used for agriculture. Extensive usage of land due to modernization in agriculture has resulted in the climate change and threatens biodiversity. Hence, it is necessary to reduce the usage of resource-intensive products and bring sustainability in existing cropping systems. Area under crop cultivation is decreasing day by day mainly due to population pressure as well as because of land degradation and changes in land-use patterns. Furthermore, in future, intensive agricultural practices will be questionable because of diminishing stocks of natural resources (e.g., fossil fuels and nutrients). Similarly, ongoing patterns of environmental changes will seriously hamper agricultural production as the intensity of extreme events across the globe has increased at a rapid pace. Degradation of natural resources, loss of biodiversity, and climate change due to anthropogenic activities are big concerns for future food, fuel, and fiber production. Unsustainable cropping systems in the form of intensive monoculture farming have resulted in the destruction of flora and fauna. Thus, it is necessary to bring sustainability in the agricultural system as agriculture is also a major contributor of greenhouse gases. The option can be regenerative agriculture that is an approach to farming and land management that aims to restore and enhance the health and vitality of ecosystems while also improving agricultural productivity. It is often seen as a response to the environmental and sustainability challenges associated with conventional industrial agriculture. Other terms used for "regenerative" agriculture include sustainable agriculture, green agriculture, alternative agriculture, agroecological farming, biodynamic agriculture, carbon farming, nature-inclusive farming, conservation agriculture, and organic regenerative agriculture. Models can be used to quantify the efficiency of cropping systems as well as to design a sustainable agriculture system. They can also assess agricultural production and environmental risks. Similarly, crop models can help to design adaptation (e.g., agronomic, nature based, technological, and financial) options under future changing climate. This book, ***Cropping Systems Modeling Under Changing Climate***, presents the views of agricultural experts. The 15 chapters—contributed by internationally recognized scientists from Asia and the USA—have been written under the theme of climate change, cropping systems, and modeling. The vast array of subject areas discussed in the book ranges from sustainable agriculture to process-based modeling, from main cropping systems to new proposed cropping systems, from resource-intensive systems to resource conservation system, and from quantification of climate risk to suggestions of adaptation options under changing climates to have sustainable production. As far as possible, the language of the chapters has been kept simple so that educated nonexpert readers may enjoy reading and may benefit from the information provided herein. This book will serve as an educational tool for budding scientists, will provide a comprehensive overview for advanced researchers, and will lay guidelines for important policy decisions.

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Contents

About the Authors

Mukhtar Ahmed's research focuses on the application of IoT in agriculture and impact of climate change on crop ecology, crop physiology, cropping system, and rain-fed ecosystem management. He specializes in environmental sciences, precision agriculture, agro-ecosystem modeling, climate change, and climate variability, with extensive teaching and research experience. His work has an impact factor of over 500, with an H-Index of more than 40. He has published 05 books. According to Mendeley Data, his name was listed among top 2% of renowned researchers in the world in 2022. Dr. Ahmed has research experience from Sydney University, Australia, Swedish University of Agricultural Sciences, Sweden, and APCC South Korea where he worked on the application of process-based modeling and remote sensing. Dr. Ahmed was part of the Regional Approaches for Climate Change (REACCH) project in the USA and was part of Washington State University where he developed multi-model ensemble approaches to minimize the uncertainties in modeling. He is a project co-leader in the Model Calibration Group of the Agricultural Model Intercomparison and Improvement Project (AGMIP) focusing on wheat, maize, evapotranspiration, and CO_2.

Sajjad Hussain is working as a Professor of Horticulture in the Faculty of Agricultural Sciences & Technology at Bahauddin Zakariya University, Multan, Punjab, Pakistan. He earned his Ph.D. in 2011 at the University of Corsica Pascale Paoli, France. Apart from teaching various graduate and postgraduate horticultural courses, his primary areas of research are plant physiology under abiotic stresses, management of nutrient uptake of horticultural crops, and plant adaptation under climate uncertainty. The overall aim of his research is to understand the underlining mechanisms for the management of abiotic stresses (salt, drought, temperature, waterlogging, etc.) by combining physiological, eco-physiological, molecular, and biogeochemical approaches. He has been working in the field of horticulture for the last 15 years. He has published over 70 peer-reviewed publications, one edited book, over 40 book chapters, and several conference papers. He has successfully supervised three Ph.D. students and 25 M.Phil. students. He has been involved as principal and coprincipal investigator in various research grants worth around 25 million PKR from different funding agencies. He is also actively working as a reviewer for different impact factor journals.

Shakeel Ahmad is a Professor of Agronomy at the Institute of Agronomy (IOA), Bahauddin Zakariya University Multan, Pakistan. In 2006, he received his Ph.D. from the University of Agriculture, Faisalabad, Pakistan. Later, he completed his postdoctoral research from the University of Georgia, USA. He joined as a Lecturer in the Department of Agronomy, Bahauddin Zakariya University, in October 2002. He was promoted to Professor in 2016. He has devoted himself to teaching and researching in the field of arable crops, especially focused on crop modeling, climate change impact assessment, and adaptation strategies. He has published over 200 articles and 150 book chapters. Furthermore, he has published six books [(1) *Cotton Production and Uses*; (2) *Modern Techniques of Rice Crop Production*; (3) *Citrus Production: Technological Advancements and Adaptation to Climate Change*; (4) *Disaster Risk Reduction in Agriculture*; (5) *Biotechnology and Omics Approaches for Bioenergy Crops*; and (6) *Principles of Field Crop Production*]. His publications received over 7500 citations with an h-index of 50 (according to Scopus). He is an editor and reviewer of many peer-reviewed international journals. He is also an active and life member of professional societies like Pakistan Society of Agronomy and Pakistan Botanical Society. He has attended and presented papers and posters in national and international conferences in different countries.

Ghulam Abbas is working as an Agriculture Officer in the Punjab Agriculture Department. He holds a Ph.D. in Agronomy from Bahauddin Zakariya University. His areas of interest encompass agronomy, climate change and agro-meteorology, crop growth modeling, remote sensing, and geographic information system (GIS). He has expertise in cropping system models "Decision Support System for Agrotechnology Transfer (DSSAT) and The Agricultural Production Systems sIMulator (APSIM)." He has more than 5 years of research experience in different research projects. He has published over 50 articles in national and international peer-reviewed journals and books in his areas of expertise. Additionally, he serves as a reviewer for numerous esteemed national and international journals.

Gerrit Hoogenboom is a Preeminent Scholar in the Global Food Systems Institute and Professor of Agricultural and Biological Engineering at the University of Florida, USA. Prior to his appointment at the University of Florida he was Professor of Biological Systems Engineering and Director of the AgWeatherNet Program at Washington State University, USA, specializing in providing near real-time weather information for decision support by growers and producers. Professor Hoogenboom has over 30 years of experience in the development of crop simulation models and decision support systems. Applications range from freeze forecasting to climate variability and climate change, water resources management, biofuels, economic and environmental sustainability, and food and nutrition security. He currently coordinates the development of the Decision Support System for Agrotechnology Transfer (DSSAT), one of the most widely used crop modeling systems across the world. He frequently organizes and facilitates international training workshops on crop modeling and decision support systems. He has published over 500 scientific papers in refereed journals as well as numerous book chapters and proceedings. In 2022, he was elected as a fellow of the American Association for the Advancement of Science.

Cropping Systems and Application of Models

1

1.1 Cropping Systems

Land on planet earth is mainly used for agriculture. New world map of land-use systems has been provided by Helmholtz Centre for Environmental Research (UFZ) so that appropriate measures can be taken to prevent land from destruction (Fig. 1.1) (Václavík et al. 2013). Different land-use indicators have been used to elaborate each archetype as shown in Fig. 1.2. Extensive usage of land due to modernization in agriculture resulted in the climate change and threatens biodiversity. (Ahmed and Ahmad 2023; Ahmed 2023; Abbas et al. 2023; Liu et al. 2023; Ahmed et al. 2022a; Ahmed et al. 2022b; Nadeem et al. 2022; Ahmed 2020; Khan et al. 2020; Asseng et al. 2019; Ahmed et al. 2017; Jabeen et al. 2017; Aslam et al. 2013; Ahmed et al. 2012). Hence, it is necessary to reduce the usage of resourc e-intensive products and bring sustainability in existing cropping systems.

Cropping system refers to the crops and crop sequences and the management techniques used on particular piece of land over a period of years. Similarly, cropping systems refer to the practices and strategies employed in the cultivation of crops within a specific agricultural system. Furthermore, multiple cropping systems refer to the practice of growing two or more crops on the same piece of land within a single growing season. Multiple cropping, defined as harvesting more than once a year, is a widespread land management strategy in tropical and subtropical agriculture. It is a way of intensifying agricultural production and diversifying the crop mix for economic and environmental benefits (Waha et al. 2020). It involves carefully planning and managing the timing, spacing, and selection of crops to maximize productivity and resource utilization. These systems involve decisions regarding crop selection, planting techniques, intercropping, crop rotation, and management practices. Different cropping systems are designed to optimize productivity, resource-use efficiency, soil health, and sustainability. Here are some commonly practiced cropping systems:

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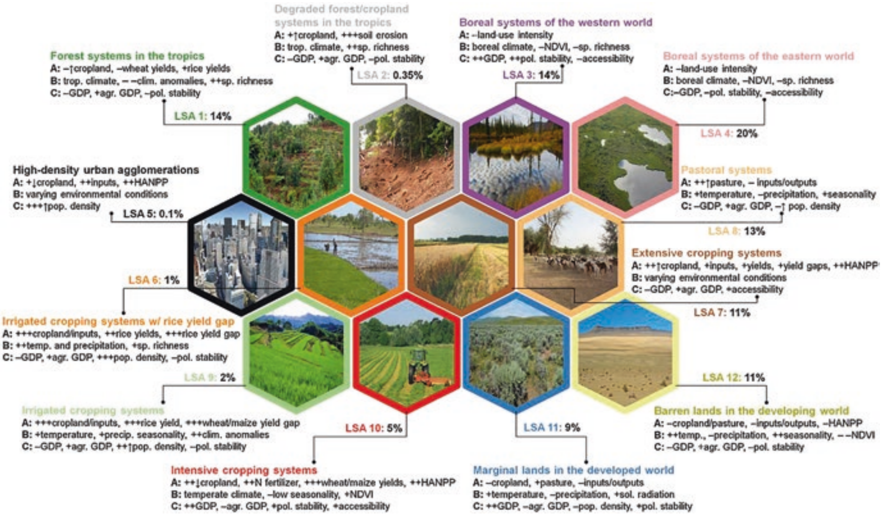


Fig. 1.1 Global map showing land usage. (Source with permission: Václavík et al. 2013; https://www.ufz.de/index.php?en=35349)

1. Monoculture

   Monoculture involves the cultivation of a single crop species on a given piece of land. It is a straightforward system that allows for focused management practices and specialized equipment. However, monoculture can lead to increased pest and disease pressures and nutrient imbalances over time.

2. Double Cropping

   Double cropping involves growing two different crops successively on the same field within a year. After harvesting the first crop, a second crop with a different growth cycle is planted to take advantage of the remaining growing season. This system is common in regions with long growing seasons and sufficient moisture.

3. Crop Rotation

   Crop rotation involves growing different crops in a planned sequence over multiple seasons or years. This system helps to break pest and disease cycles, enhance soil fertility, and reduce weed pressure. Crop rotation can also improve nutrient utilization and reduce the need for chemical inputs.

4. Interplanting

   Interplanting, also known as mixed cropping, involves growing multiple crops together in the same field, either in rows or mixed randomly. The crops are selected based on their compatibility, growth habits, nutrient requirements, and pest interactions. Interplanting can provide benefits such as pest control, efficient use of resources, and increased biodiversity.

5. Strip Cropping

   Strip cropping involves alternating strips of different crops on the same field. It is often practiced on sloping land to reduce soil erosion by breaking up the flow of water. The strips can be planted with different crops or cover crops to provide ground cover and stabilize the soil.

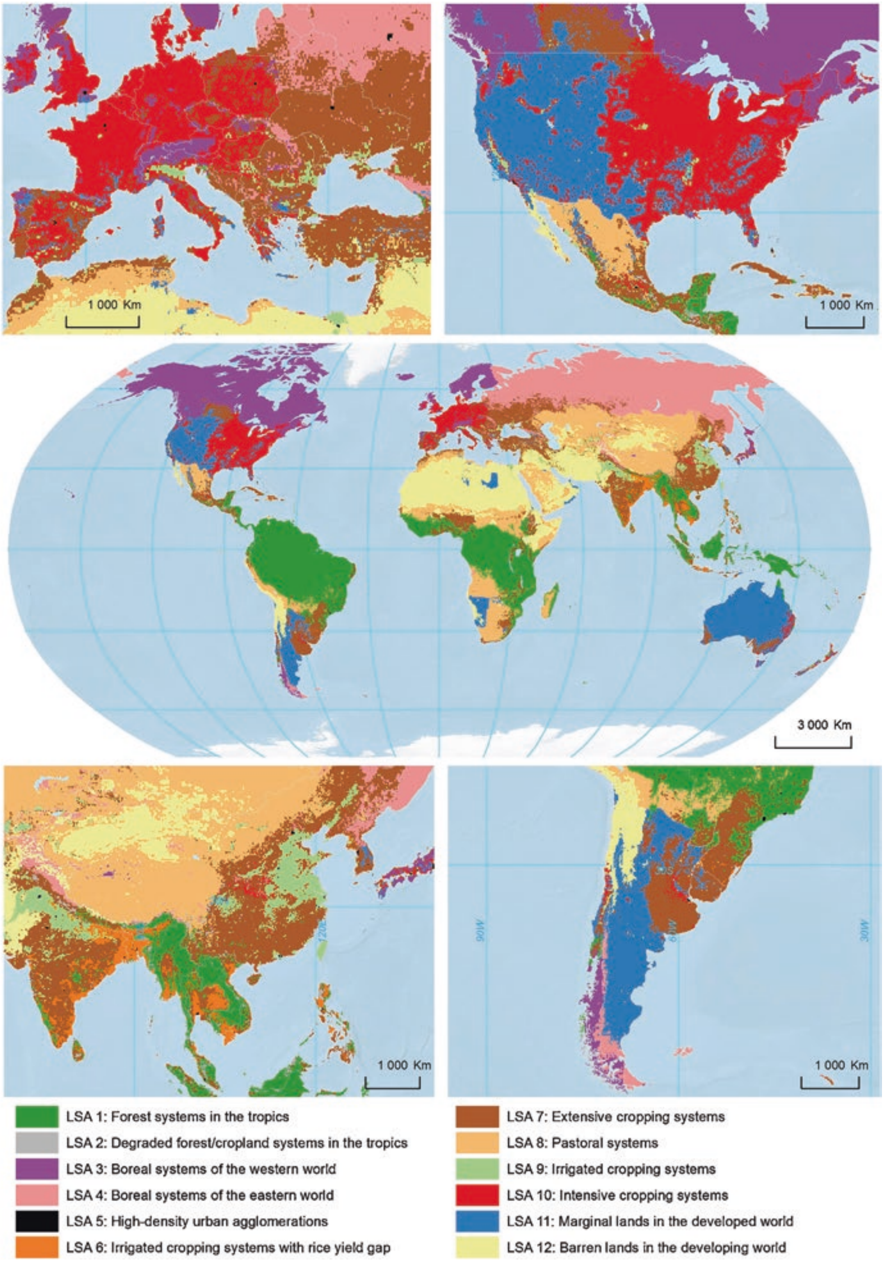


Fig. 1.2 Land system archetype overview showing major land-use intensity indicators (**a**) and environmental (**b**) and socioeconomic factors (**c**) that best characterize each archetype. Here, + and − signs show above and below global average. (Source with permission: Václavík et al. 2013)

6. Intercropping

   Intercropping is the simultaneous cultivation of two or more crops in close proximity on the same field. It maximizes the use of available space, sunlight, and soil resources. Intercropping can provide complementary benefits such as pest control, improved nutrient utilization, and enhanced soil structure. Examples include growing legumes with cereals or planting nitrogen-fixing crops alongside cash crops.
7. Relay Cropping

   Relay cropping involves the overlapping of two or more crops in the same field, where the second crop is planted before the first crop is harvested. This system optimizes the use of time and resources, allowing for increased overall productivity. Relay cropping involves planting a second crop before the first crop is harvested. The two crops grow together for a period, utilizing the available resources simultaneously. It optimizes land use and allows for increased overall productivity by extending the growing season and maximizing resource utilization. For example, a winter crop can be relayed with a spring crop to fully utilize the growing season.
8. Agroforestry Systems

   Agroforestry systems integrate trees with crops in a deliberate manner. This system provides multiple benefits such as increased biodiversity, improved microclimate, soil conservation, and additional income streams from tree products. Examples include alley cropping, where rows of trees are planted between rows of crops, or silvopastoral systems, combining trees, crops, and livestock.
9. Perennial Cropping

   Perennial cropping systems involve the cultivation of long-lived plants, such as fruit trees or perennial grasses. This system requires less frequent replanting, reduces soil erosion, and can provide stable yields over an extended period. Perennial crops often require specialized management techniques and longer establishment times.
10. Conservation Agriculture

    Conservation agriculture aims to minimize soil disturbance, maintain permanent soil cover, and promote crop diversity. This system emphasizes minimal tillage, residue management, and use of cover crops. Conservation agriculture helps improve soil health, reduce erosion, enhance water retention, and increase long-term sustainability.
11. Mixed Farming

    Mixed farming involves integrating crop production with livestock rearing. The crops and livestock are managed together, allowing for nutrient cycling, efficient resource utilization, and increased farm productivity.
12. Regenerative Agriculture

    Regenerative agriculture is an approach to farming and land management that aims to restore and enhance the health and vitality of ecosystems while also improving agricultural productivity. It is often seen as a response to the environmental and sustainability challenges associated with conventional industrial agriculture (Fig. 1.3). Other terms used for “regenerative agriculture” include

Fig. 1.3 Principles of regenerative agriculture

sustainable agriculture, green agriculture, alternative agriculture, agroecological farming, biodynamic agriculture, carbon farming, nature-inclusive farming, conservation agriculture, and organic regenerative agriculture (Newton et al. 2020).

Here are some key principles and practices associated with regenerative agriculture:

(i) Soil Health

Regenerative agriculture places a strong emphasis on improving and maintaining soil health. Healthy soils are essential for productive agriculture and have numerous benefits for the environment. Practices such as minimal or no-till farming, cover cropping, and crop rotation are used to build soil organic matter, improve soil structure, and increase nutrient availability.

(ii) Biodiversity

Promoting biodiversity is a central component of regenerative agriculture. Diverse ecosystems are more resilient and can provide natural pest control, pollination, and enhanced nutrient cycling. Farmers may plant hedgerows, establish wildlife corridors, or create habitat for beneficial insects to support biodiversity.

(iii) Reduced Chemical Inputs

Regenerative agriculture seeks to minimize the use of synthetic pesticides and fertilizers, which can have negative environmental impacts. Instead, it encourages integrated pest management, where natural predators are used to control pests, and nutrient management practices like composting and organic matter incorporation are employed.

(iv) Agroforestry

Integrating trees and other perennial vegetation into agricultural systems is a common practice in regenerative agriculture. Agroforestry can provide multiple benefits, including carbon sequestration, improved soil health, and additional income streams for farmers through products like fruits and nuts.

(v) Water Management

Sustainable water management is crucial in regenerative agriculture. Practices like water harvesting, contour farming, and use of cover crops can help reduce soil erosion, enhance water retention, and improve water quality.

(vi) Holistic Management

Regenerative farmers often employ holistic management approaches, which involve considering the whole ecosystem, including soil, plants, animals, and people, in decision-making processes. This helps ensure that farming practices are sustainable in the long term.

(vii) Carbon Sequestration

One of the significant benefits of regenerative agriculture is its potential to sequester carbon dioxide from the atmosphere and mitigate climate change. Healthy soils can act as carbon sinks, storing carbon in the form of organic matter.

(viii) Local and Sustainable Food Systems

Regenerative agriculture often supports local and sustainable food systems by encouraging the production of food closer to the point of consumption. This reduces the carbon footprint associated with food transportation and fosters community resilience.

(ix) Adaptive Management

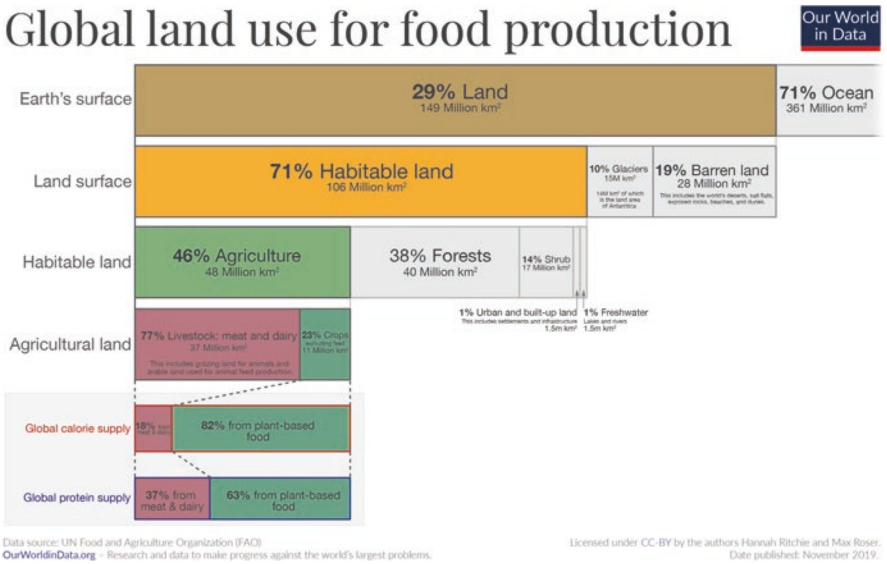
Regenerative farmers are encouraged to adapt their practices based on local conditions and feedback from the land. This flexibility allows for a more responsive and sustainable approach to agriculture.

Overall, regenerative agriculture is driven by the goal of creating farming systems that are not only economically viable but also ecologically and socially responsible. It seeks to promote agricultural practices that regenerate and enhance the health of ecosystems, increase resilience to environmental challenges, and provide a foundation for sustainable food production. However, choice of cropping system depends on factors such as climate, soil conditions, available resources, market demand, and farmer preferences. Integrated approaches that combine multiple cropping systems and sustainable practices are increasingly being adopted to optimize productivity, conserve natural resources, and promote agricultural resilience. These cropping systems offer advantages such as increased productivity, risk reduction, efficient resource use, and improved sustainability. However, successful implementation requires careful crop selection, proper planning, effective pest and nutrient management, and knowledge of the specific ecological requirements of the crops involved.

1.2 Global Cropping Systems

Half of the world's habitable land is used for agriculture. One-third of all land is used for cropping or animal husbandry (Fig. 1.4).

Different types of cropping systems exist across the globe based upon climatic conditions and soil properties. Waha et al. (2020) identified top five cropping



Data source: UN Food and Agriculture Organization (FAO)
OurWorldinData.org – Research and data to make progress against the world's largest problems.

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Date published: November 2019.

Fig. 1.4 Global land use for food production

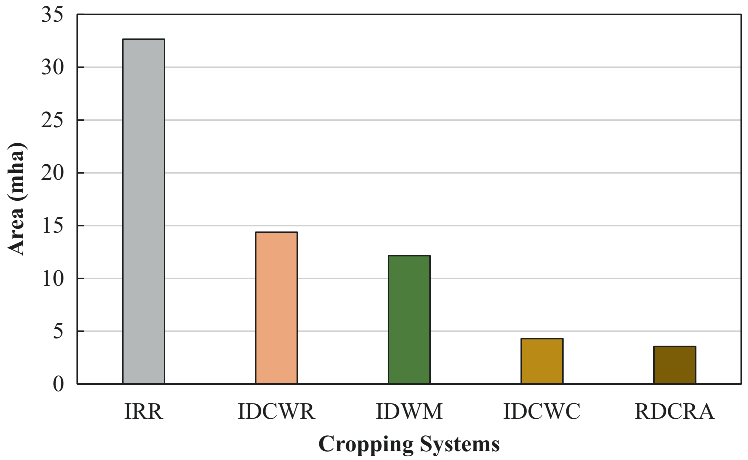

Fig. 1.5 Area of top five cropping systems: (i) irrigated rice-rice (IRR), (ii) irrigated double cropping with wheat and rice (IDCWR), (iii) irrigated double cropping with wheat and maize (IDWM), (iv) irrigated double cropping with wheat and cotton (IDCWC), and (v) rainfed double cropping with rapeseed and another annual crop (RDCRA). (Source: Waha et al. 2020)

systems based on physical area, and it includes (i) irrigated rice-rice (IRR), (ii) irrigated double cropping with wheat and rice (IDCWR), (iii) irrigated double cropping with wheat and maize (IDWM), (iv) irrigated double cropping with wheat and cotton (IDCWC), and (v) rainfed double cropping with rapeseed and another annual crop (RDCRA) (Fig. 1.5). These systems account for greater than 50% of global

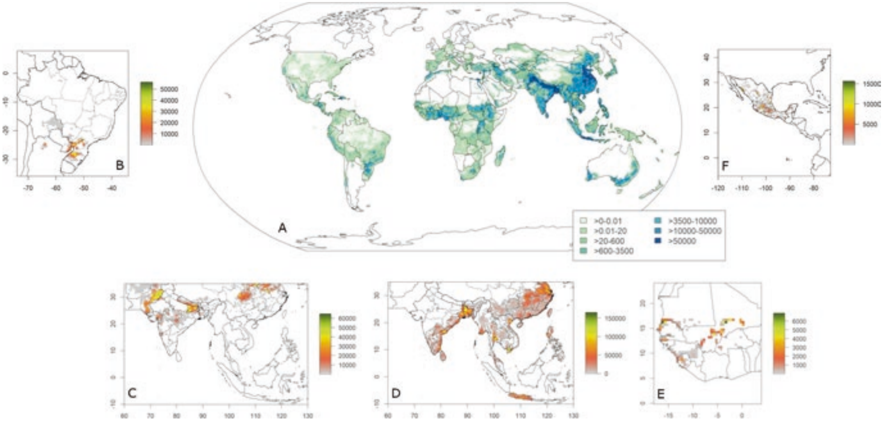

Fig. 1.6 Physical area (hectare) of multiple-cropping systems per 30 arc-min grid cell, 1998–2002. (**a**) Global multiple cropping area. (**b**) Rainfed soybean-wheat double-cropping system in South America. (**c**) Irrigated wheat-rice and rice-rice (**d**) double-cropping system in South, East, and Southeast Asia. (**e**) Irrigated rice-rice double-cropping system in West Africa. (**f**) Irrigated maize-wheat double-cropping system in Central America. White areas indicate locations with total crop area less than or equal to 1% of the grid cell area

cropland when combined with monocultures of wheat, maize, rice, soybean, and pulses, which occupies 468.8 Mha. Furthermore, their estimate reported 134.4 Mha land under multiple cropping, which is 12% of total global crop land as shown in Fig. 1.6. Similarly, 40% of global irrigated crop land and 5% of global rainfed cropland are under multiple cropping. Unsustainable farming practices/systems and urbanization have shown great impacts on natural resources (Hoffmann et al. 2019).

Sustainable agriculture is key to preserving these resources, protecting biodiversity, and producing food feed and bioenergy (Snapp 2017; Snapp and Pound 2017). It is essential to identify new pathways, which can help us to design sustainable agriculture in both temperate and tropical regions under changing climate (Malézieux 2012). A three-step framework for designing cropping systems from nature was proposed by Malézieux (2012) as shown in Fig. 1.7.

The first step is observation of natural ecosystem in the area, and it includes identification of all biodiversity in the target area in consultation with the local farmers. Second step includes experimentation based on the knowledge established in step one. This should answer the following questions:

(i) What are the issues in the existing cropping systems, and what levels of performances/services existing cropping systems fail to deliver?
(ii) What levels of performances/services new cropping systems can achieve?
(iii) What life-forms and species are needed in the new proposed system?

Specific or a combination of practices are required to design new novel cropping systems, and these include rotations, intercropping, mixed cropping, cover crops,

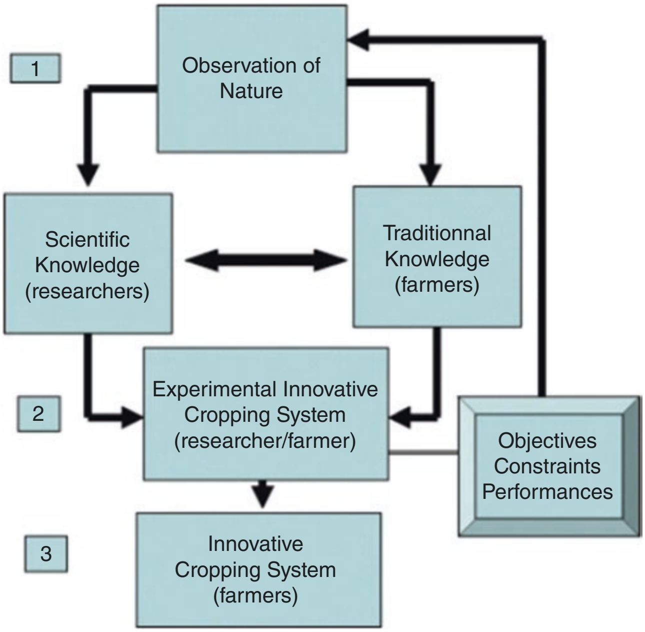

Fig. 1.7 Framework for designing cropping systems from nature. (Source: Malézieux 2012)

service plants, green manuring crops, composting, conservation tillage, perennial cropping, and agroforestry. However, success of all these proposed new cropping systems depends on how well farmers can incorporate or adopt these practices at field scale so that it can satisfy all three indicators, i.e., ecology, economy, and society (Step 3). Furthermore, sustainability in agricultural systems is possible by providing viable solutions to different economic, environmental, and production issues (Fresco 2009; Park and Seaton 1996). Fundamental measures can be reduction in greenhouse gas emissions and improved energy efficiency (Dyer and Desjardins 2003). In general, energy requirement of the agriculture sector is low as compared to other sectors, but to achieve economic sustainability and reduction in greenhouse gas emissions, identification of systems with low energy requirements is needed. Alluvione et al. (2011) estimated the energy flows of wheat-maize-soybean-maize rotation under three different cropping systems, i.e., low input integrated farming (LIIF), integrated farming following European regulations (IFFER), and conventional farming (CF). Results showed that minimum tillage with balance N fertilization can reduce energy inputs by 11% and 65%, respectively. They further highlighted large differences among crops in energy efficiency, i.e., soybean 4.1 MJ kg^{-1} grain, maize 2.2 MJ kg^{-1} grain, and wheat 2.6 MJ kg^{-1} grain, and suggested that crop management in rotation is equally important in determining the energy efficiency of a cropping system. Different energy indicators were used to check the efficiency of cropping systems as shown in Table 1.1. It was observed that

Table 1.1 Energy indicators of the different crops in the differing cropping systems

		Cropping systems			
Energy indicators	Crops	Low input integrated farming (LIIF)	Integrated farming following European regulations (IFFER)	Conventional farming (CF)	Average
Indicator of immediate removal (IIR)	Wheat	3.1	2.7	2.4	2.7
	Maize	0.8	0.9	0.8	0.8
	Soybean	0.5	0.6	0.4	0.5
	Average	**1.5**	**1.4**	**1.2**	**1.4**
Energy intensity (EI) (MJ kg^{-1} grain)	Wheat	2.1	2.6	3.3	2.7
	Maize	1.9	2	2.6	2.2
	Soybean	3.4	3.7	5.3	4.1
	Average	**2.5**	**2.8**	**3.7**	**3.0**
Energy-use efficiency (EUE)	Wheat	18.8	15.5	12.3	15.5
	Maize	10.2	9.8	7.5	9.2
	Soybean	7.3	6.7	4.7	6.2
	Average	**12.1**	**10.7**	**8.2**	**10.3**
Net energy (NE) (GJ ha^{-1} grain)	Wheat	188.3	184.1	174.4	182.3
	Maize	181.4	189.5	189.1	186.7
	Soybean	60.7	64.2	51.4	58.8
	Average	**143.5**	**145.9**	**138.3**	**142.6**
Environmental efficiency of support energy (EESE)		11.7	7	4.3	7.7
Net environmental energy (NEE)		173.8	102.8	74.2	116.9

energy-use efficiency of LIIF and IFFER was increased by 32.7% and 31.4%, respectively, as compared to CF.

Rice-wheat cropping system (RWCS) is feeding a large population of Indo-Gangetic Plains (IGPs) of South Asia. However, sustainability of RWCS has been a big concern since past few decades due to open-field burning of rice residues. This burning leads to environmental pollution due to emissions of greenhouse gases as shown in Fig. 1.8. This also deteriorates soil health and increases C footprints. In Asia, mostly rice is harvested mechanically, which leaves large amounts of straw (~600–800 million tons of rice straw) and stubble in field. Global production of rice straw is around 800–1000 million tons. In the north-western part of India, ~500 million tons of crop residues are produced annually. However, in Pakistan, ~16 million tons of paddy straw is produced annually, of which 60% is burnt. It has been reported that 1.0 Mg dry mass straw releases 1515 kg CO_2, 92 kg CO, 2.7 kg CH_4, and 0.07 kg N_2O. Additionally, 1.0 Mg of rice straw burning leads to loss of 5.5 kg N, 2.3 kg P, 25 kg K, and 1.2 kg S from the soil, thus deteriorating soil health (Singh et al. 2023; Pathak et al. 2011; Andreae 2019). Thus, management of rice straw is an utmost important task to have sustainable cropping system.

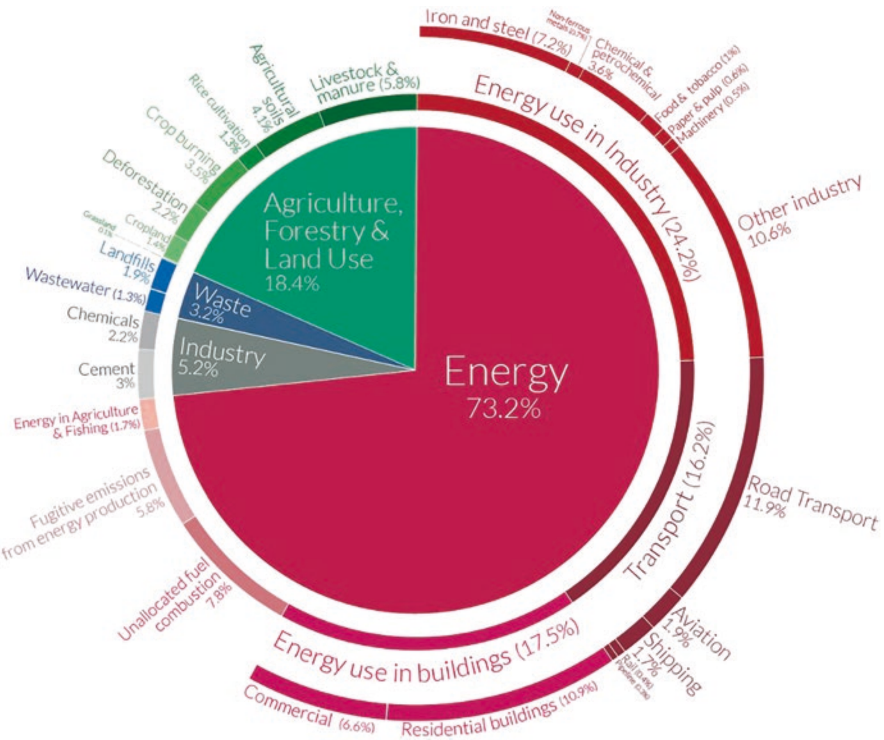

Fig. 1.8 Global greenhouse gas emissions by sector. (Source: Our world in data)

Different ways have been suggested to utilize rice straw and minimize greenhouse gas emissions. These include (i) rice straw mushroom production, (ii) rice straw silage for cattle feed, (iii) mechanized composting of rice straw, (iv) rice straw for improved soil fertility, (v) alternative source of energy and bioethanol production (Swain et al. 2019; Samaddar et al. 2017), (vi) pulping and paper making (Nayeem et al. 2023), (vii) source of silicon (Nayeem et al. 2023; Ma and Takahashi 2002), and (viii) animal feed (Khir and Pan 2019).

1.3 Cropping System Modeling

Models can be used to quantify the efficiency of cropping systems. They can also assess agricultural production and environmental risks. Similarly, crop models can help to design adaptation (e.g., agronomic, nature based, technological, and financial) options under future changing climate. Different process-based cropping system models have been developed to suggest sustainable cropping system. These include Agricultural Production Systems Simulator (APSIM), AquaCrop, CropSyst, Daisy, Decision Support System for Agrotechnology Transfer (DSSAT), DeNitrification-DeComposition (DNDC), EPIC, FarmSim, Farm ASSEssment Tool

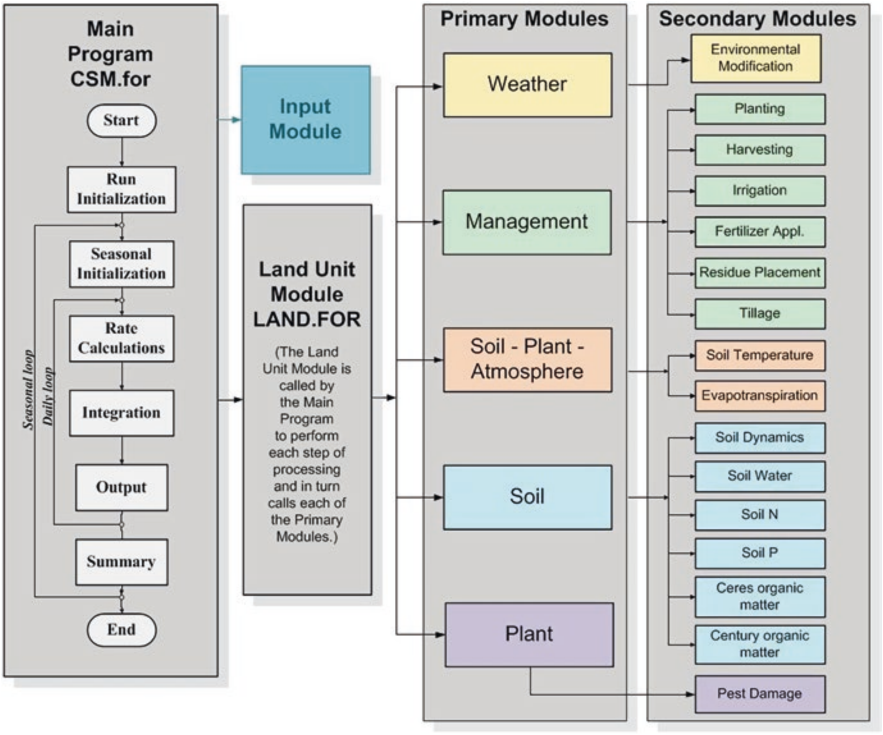

Fig. 1.9 Schematic view of DSSAT cropping system model. (Source: DSSAT.net)

(FASSET), HERMES, STICS, SUCROS, SWAP, and WOFOST. DSSAT is a well-known cropping system model, and it contains more than 40 crop models derived from CERES-Wheat, CERES-Maize, PNUTGRO, and SOYGRO. Schematic diagram of DSSAT illustrates connections between the primary and secondary modules (Fig. 1.9).

Gao et al. (2022) used DSSAT to simulate the impacts of crop rotation on crop evapotranspiration, percolation, water-use efficiency, and yield. Results showed that the model simulated groundwater with good accuracy. Their results suggested that DSSAT is a very useful tool for selecting suitable cropping systems based on the water use for local farmers. Liu et al. (2017) simulated wheat yield and soil organic carbon under a wheat-maize cropping system using DSSAT. They suggested that if the model is calibrated accurately, then it can be a useful tool for assessing and predicting different parameters of cropping system. Irrigation management in the cropping system research is very important as it can help to minimize water losses. DSSAT can help to choose best irrigation management practices under different climates as concluded in earlier work (Malik and Dechmi 2019; Montoya et al. 2020; Amouzou et al. 2019; Mehrabi and Sepaskhah 2020; Shelia et al. 2019; Araya et al. 2017; Attia et al. 2016; Galmarini et al. 2024; Wahab et al. 2024; Ahmed et al. 2019; Liu et al. 2019; Asseng et al. 2019; Ahmed et al. 2017, 2016, 2014a, b and

Ahmed and Hassan 2011; Jiang et al. 2016; He et al. 2013). DSSAT is a very useful tool to improve different agronomic management operations, e.g., irrigation timing under water-limited conditions (Attia et al. 2016; Araya et al. 2017), impact of climate change and planting date (Abbas et al. 2023; Zhang et al. 2023), N fertilizer management (Malik and Dechmi 2020; Amouzou et al. 2019), and productivity of forage-based cropping system (Baath et al. 2021). Incorporation of legume forage in the dryland cropping system could help to provide nutritious forage for livestock as it will help to minimize N application, protect soil erosion, and improve precipitation-use efficiency. Baath et al. (2021) conducted a study using DSSAT to evaluate the impact of forage soybean of different maturity groups on winter wheat and double-cropping systems in comparisons to the fallow-wheat system. The model was calibrated and validated using field data of crop yield and evapotranspiration. Results showed that mid-maturity group soybean gives higher yield and water-use efficiency as compared to late-maturing group. Figure 1.10 shows the simulation performance of DSSAT to simulate biomass and evapotranspiration (ET). However, double-cropping forage soybean and winter wheat resulted in the reduction in winter wheat yield and higher seasonal ET, but it can be compensated due to economic competitiveness and other ecological benefits of double-cropped forage soybean-wheat systems.

He et al. (2021) used three process-based models, i.e., DNDC, DayCent, and DSSAT, to simulate soil carbon sequestration under diverse cropping systems in the semiarid prairies of western Canada. Higher soil organic carbon (SOC) was simulated for the cropping systems where there was higher incorporation of residues or fixation of N as compared to fallow-wheat systems. Better SOC was estimated by DNDC, while DSSAT predicted yield with good accuracy. Furthermore, they suggested that diverse cropping systems, e.g., canola and legume, have higher potential to store SOC as compared to traditional cropping systems. DNDC has been used by different researchers to simulate greenhouse gas emissions and SOC under different agroecosystems (Waldrip et al. 2013; Li et al. 2012; Giltrap et al. 2010; Wang et al. 2022). Based on DNDC's ability to simulate N_2O emissions in response to different agronomic managements, DNDC can be recommended as a valuable tool for designing mitigation strategies.

APSIM is also a well-known widely used cropping system model developed by Agricultural Production Systems Research Unit (APSRU), CSIRO, and state of Queensland Government agencies. Vogeler et al. (2023) applied APSIM model to simulate crop rotation to check N leaching, N uptake, and crop yield and concluded that the model showed good results regarding crop rotation. Their results suggested that APSIM is the best tool to work with crop rotation to reduce the amount of N leaching by reducing fertilization rates and to increase the yield and uptake of N for the crops. He et al. (2023) used pre-validated APSIM to assess the combined influences of cowpea cover crops and three residue retention levels on soil water balance, SOC, N dynamics, crop yield, and gross margin across six crop rotation systems during the historical period (1985–2020), near future (2021–2056), and far future (2057–2092) in southeast Australia. Their results showed that the use of cover crops resulted in higher SOC and yield, reduced N loss, and better uptake of

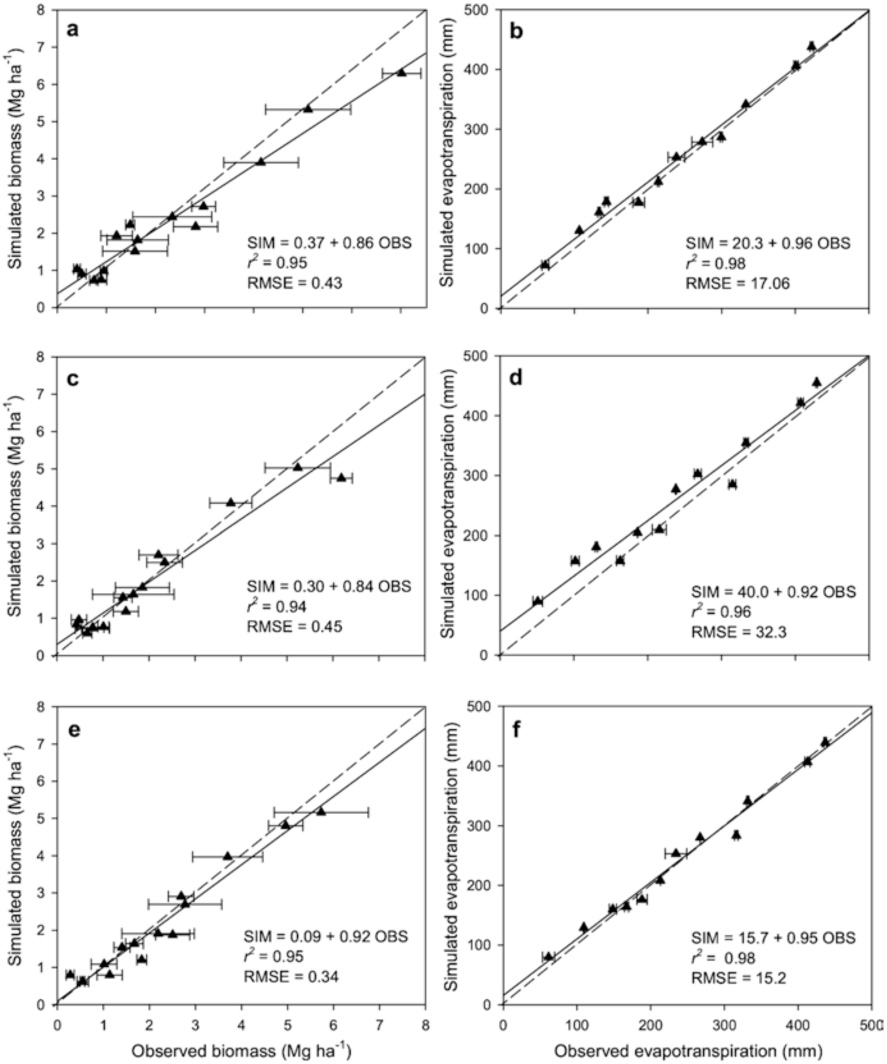

Fig. 1.10 Simulated versus observed biomass and evapotranspiration values for three forage soybean cultivars: (**a, b**) Donegal MGV, (**c, d**) Derry MGVI, and (**e, f**) Tyrone MGVII, using data from field studies conducted at the USDA-ARS Grazinglands Research Laboratory near El Reno, Oklahoma, USA. (Source: Baath et al. 2021)

N in cereals as compared to legume crops. Thus, they concluded that sustainability in crop production with environmental co-benefit is possible by adopting cover crops in the dryland cropping system. Pasley et al. (2023) developed mung bean APSIM next-generation model by using data from 28 diverse fields. They concluded that APSIM is a robust model as it successfully captured the dynamics of crop response to sowing dates, water/irrigation regimes, and climate. Hence, APSIM is a useful tool to evaluate crop sowing dates, total water requirement, and total fertilizer rate of the crop and improve breeding strategies and climate. It is also a useful tool for the farmer to help them to examine options for improving management required for the crop and assess all the production risk across the growing regions. Bana et al. (2023) used APSIM to analyze 37 years (1984–2022) of diverse conservation agriculture (CA) scenarios on productivity, sustainability, and carbon footprints in the rice-wheat cropping system (RWCS). The study highlighted that APSIM was able to capture the impact of CA on SOC, carbon sequestration, and water productivity in RWCS. Yang et al. (2020) used APSIM to evaluate the impact of perennial legumes on the economic profitability, hydrological balance, and agronomic productivity of cropping system of Loess Plateau of China using different climate change scenarios. Five different cropping systems ((i) continuous maize (M), (ii) continuous winter wheat (W), (iii) continuous lucerne (L), (iv) maize-wheat-soybean rotation (MWS), and (v) lucerne (4 years)-winter wheat (2 years) rotation (LW)) were investigated under five series of temperature and precipitation change scenarios. The results showed that LW system has the greatest potential for producing acceptable yield and economic profit under future temperature and precipitation scenarios for this local environment. Similarly, these different process-based models can be used to suggest on-farm different adaptation options as elaborated by Farrell et al. (2023). These include agronomic, nature based, and technological adaptation as shown in Table 1.2.

Pathak et al. (2011) have developed InfoRCT (Information on Use of Resource-Conserving Technologies) that can establish input-output relationships in RWCS. It can simulate GHG emissions and system productivity in response to different crop management practices.

1.4 Conclusion

Land use and climate change are closely interconnected and have significant impacts on each other. Land use refers to how land is utilized, developed, and managed for various purposes, including agriculture, urbanization, forestry, and conservation. Cropping systems: Unsustainable cropping systems are agricultural practices that are detrimental to the long-term health of the environment, the productivity of the land, and often the economic well-being of farmers. These systems may prioritize short-term gains but result in negative consequences over time. Addressing unsustainable cropping systems typically involves adopting more sustainable and environmentally friendly agricultural practices. Sustainable agriculture promotes practices like crop rotation, reduced chemical input use, agroforestry, integrated pest management, and conservation tillage. These approaches aim to protect the environment, maintain or improve soil health, conserve biodiversity, and ensure long-term food security while also considering the economic viability of farming operations. Transitioning to sustainable cropping systems is essential to meet the challenges of feeding a growing global population while protecting natural resources