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Achieving Sustainable Intensification of Crop Production: A Review Traditional Knowledge and Technology

Yessirkepova Altyn Mahmudovna
Academy of Public Administration under the President of the Republic of Kazakhstan, Shymkent' Branch, Professor
Doctor of economics
altyn.makhmudovna@gmail.com

Akhmetova Gulnara Zhaksykeldyevna
Doctoral student PhD M. Auezov South Kazakhstan State University
gulnaraakhmetovaa@gmail.com

Aliyeva Zhanna Tynybekovna
Associate Professor, Narxoz University
PhD in economics
aliyeva.zhannaa@gmail.com

Polezhayeva Inna Sergeevna
Associate Professor, M. Auezov South Kazakhstan State University
PhD in economics
innapolezhayeva4@gmail.com

Abdulina Gulnar Abdulinkyzy
Associate Professor, Narxoz University
gulnarabdullina1@gmail.com

Correspondence address: *Academy of Public Administration under the President of the Republic of Kazakhstan, Shymkent' Branch,*

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Abstract

Sustainable crop production intensification (SCPI) is a system of boosting agricultural production without adversely affecting the environment or using additional non-agricultural land for cultivation. Numerous farming methods and technologies, adapted to local economy, culture and traditions, exist worldwide which can potentially improve crop resilience, and intensify crop production by improving yields and production efficiency without negatively affecting the environment and can be combined with modern science based technologies for synergistic effects. It is important to raise farmers' awareness of these economically and ecologically sustainable practices for their gradual acceptance and adoption and further refinements.

To meet the challenge of producing enough food to feed the growing population while preserving the environment and maintaining the ecological balance, it is important to combine farmers' local knowledge with science-based structured knowledge. In light of rapidly degrading natural resources and increasingly stressed local and global ecosystems, it becomes imperative to embrace more eco-friendly and sustainable agricultural practices while maintaining current yields and then gradually move in the direction of yield increases. It is becoming increasingly apparent that indiscriminate use of agrochemicals and energy-intensive processes is not sustainable and strategies to minimize the dependence of agricultural production on external inputs and non-renewable energy sources are urgently needed. Since smallholder farmers have a major share of arable land globally, it is also important to focus on research and development and policy formulation efforts to develop smallholder-friendly technologies and policies. In this paper, we discuss the various agricultural practices and technologies that hold potential for sustainably increasing crop production, required to meet the growing demand for food by the increasing population, without further damaging the environment.

Keywords: *Sustainable crop production, precision agriculture, conservation agriculture agroforestry, mixed cropping, rainwater harvesting*

Introduction

The technology made available by the Green revolution (GR) of 1960s has played an important role in meeting the challenges posed by the growing population and increasing scarcity of arable land. Currently, we are producing more food than required to feed the world's population. On the other hand, the population is increasing at a rapid pace, and it is estimated that by 2050 up to 70-100% more food will be required to feed the world population (FAO, 2009). The technological advancements of the GR helped achieve remarkable crop yields per hectare in developing countries. For instance, between1960-2000 the yields rose 208% for wheat, 109% for rice, 157% for maize, 78% for potatoes, and 36% for cassava (FAO, 2004). However, this technology has also led to many environmental and ecological problems, which are now seriously threatening the structure of the natural resource base on which food production depends.

The soil quality degradation due to indiscriminate use of synthetic fertilizers and pesticides is already beginning to show its effect as slowing down of yield growth worldwide (Conway 2012; Ray et. al. 2012). Moreover, the production of synthetic inputs, an important component of the GR technology, is heavily dependent on fossil fuels for both raw materials and energy. The gradual depletion of fossil fuel reserves and other materials such as mineral deposits used for the production of fertilizers and pesticides is beginning to raise serious concerns about the sustainability of crop production using GR technology. On the socioeconomic front, the industrial agriculture has failed to reduce world hunger and malnutrition to expected levels despite surplus food. An estimated 800 million people worldwide suffer from long-term caloric insufficiency, 47 million children below 5 years of age are wasted, 14.3 million are severely wasted, and 144 million are stunted (WHO, 2020). Additionally, about a billion people are deficient in at least one nutrient essential for health, 45% of deaths in children below five years of age are linked to undernutrition and iron deficiency is estimated to cause 591000 perinatal deaths and 115000 maternal deaths globally (WHO, 2020).

Marked growth in global food production in the past half-century has dramatically decreased the proportion of the world population that is hungry, despite a doubling of the total population (World Bank, 2008; FAOSTAT, 2009). Nevertheless, malnutrition due to insufficient intake of protein, energy, and micronutrients is still prevalent. More than one in seven people in the world do not have access to sufficient energy and protein and even more suffer from micronutrient deficiency (FAO, 2009). On the other hand, the availability of cheap grains is leading to a change in dietary preference for sugar and fat-rich diets and increasing consumption of animal meat that is responsible for the rapidly increasing prevalence of heart disease, diabetes, hypertension and other lifestyle diseases (Frison 2008).

The world population is predicted to grow by over 4 billion over the next 40 years, and it is projected to increase from 7.8 billion in 2020 (Joseph, 2020) to around 9.1 billion in 2050. Most of this population growth is expected to occur in developing countries, and the largest relative population increase (120%) is expected to occur in the least developed countries (Bavel, 2013). Agricultural production needs to rise by 70% worldwide and almost 100% in developing countries to satisfy the additional food demand of the growing world population. This amounts to an additional billion tons of cereals and 200 million tons of meat, relative to the production levels of these commodities during 2005-2007. (Bruinsma, 2009).

In the past, introduction of more land for cultivation and increased exploitation of fisheries were the main response to the rise in demand for food. However, the growing population is intensifying the struggle for soil, water, and other natural resources, which along with deteriorating environment and climate change, now influences our capacity to increase food production (Godfray et al., 2010). As the competition for land and the pressure to maintain sufficient natural green cover to prevent rapid climate change increases, it is becoming progressively difficult to bring more land into cultivation. In fact, though the grain production has doubled in the last five decades, the land under cultivation has increased by only 9% (Pretty, 2008). The option of bringing new land into cultivation, particularly in Sub-Saharan Africa and South America, exists. However, the demand for land from other human operations renders it an extremely expensive if not impossible option, particularly if conservation of biodiversity and public resources supplied by the natural habitats (for example, carbon sequestration by the rain forests) are given greater significance (Balmford et al., 2005). Moreover, in the last few decades, urbanization and other human uses, desertification, salinization, and soil degradation caused by unsustainable land use have taken away the land that was formerly productive. It is imminent that there will be more losses of the natural resource base for agriculture, particularly water losses caused by climate change (IPCC, 2007).

In the past four decades, much of the rise in agricultural production is associated with better genetic capital, expanded usage of pesticides, increased input of mineral materials and greater utilization of mechanized agricultural technology powered by fossil fuel, rather than the use of additional land for crop production (Wik et. al. 2008). However, environmental pollution and ecological disturbances caused by widespread use of chemical inputs, burning of fossil fuels, and increased water usage for irrigation of hybrid varieties have caused serious damage to the environment. Sustainable agriculture intensification would help to improve environmental services and to minimize the factors driving climate change by reducing pollution and preserving the carbon locked in the soil. This review focuses on the various approaches currently being taken for the sustainable intensification of agriculture. The relevance of traditional knowledge in increasing sustainability and productivity of farms along with the principles and methods of conservation agriculture and precision agriculture are discussed. The role of genetically engineered and gene edited crops and the importance of integrated weed management (IWM) and integrated pest management (IPM) practices in sustainable crop production is also discussed.

Government policies and agricultural incentives in sustainable food production

Sustainable crop production requires planning at both pre-production and production stages. The planning and efforts at the pre-production stage, including the development of high-yielding crop varieties, high quality fertilizers, and the development and production of farm machinery etc. play an important role in the yield and sustainability of crop production. The agricultural policies of the governments, training and knowledge transfers and the incentives provided to the farmers also have a bearing on the type of crop planted, nature and type of external inputs used, yields obtained, and sustainability. These policies also determine how the environment is affected by food production. For instance, subsidies chemical fertilizers and pesticides can lead to their increased usage and the corresponding adverse effects on the environment (Liang et. al. 2019, de Derecho Ambiental 2003.). The agricultural policies along with other national policies also influence environmental services such as carbon storage, biodiversity, forest covers and the population of pollinators. The policies encouraging the cultivation of a variety of crops rather than one or two major crops are more favorable to sustainability by minimizing soil degradation and ecological disturbances. Research and innovations in agriculture, such as the development of new high yielding and drought and pest resistance varieties, preservation of germplasm of wild varieties for use in future breeding programs and improvements in the agricultural inputs such as fertilizer or crop protection products contribute towards sustainability of the crop production by preventing further land being converted for cultivation.

Agricultural Technology

Technological advancements have played an important role in scaling up the food production with the growing population. World food production has increased significantly in the last 50 years, allowing a dramatic reduction in the world's people that are hungry despite a doubling of the total population (World Bank, 2008; FAOSTAT 20-09). It is estimated that the world population will grow to about 9.6 billion by 2050 before plateauing off and about 70-100% increase in the food production will be required to meet this demand (Wold Bank 2008, Royal Society of London, 2009). Currently, we are witnessing a new agricultural revolution, driven by the technology, the first two being the industrial revolution which introduced mechanization in the agriculture and the green revolution which made available to the farmers new high-yielding hybrid varieties with increased requirement for irrigation and fertilizer inputs (Walter et al. 2017). Currently, technology is being used not only to increase the crop yields but also the sustainability of agriculture by helping farmers make timely and informed decisions on the use of external inputs. This helps in minimizing the use of these inputs and contributes towards reduction of environmental pollution and soil degradation and translates into greater profit margins for the farmers.

The technology, particularly information and communication technologies (ICTs) can play a very important role in sustainable intensification of agriculture. ICTs are already being used for reducing agricultural inputs such as fertilizers, pesticides, energy, and water (Stombaugh et. al. 2005; Shockley et. al. 2012; . ICTs are playing an important role in Precision Agriculture, a farm management approach that uses sensors to measure as many variables as possible (pH, potassium, phosphate, moisture, nitrogen, crop yield, etc.) in different locations of the farm. This location-specific data is then used for the operation of various input devices such as sprayers and seeders using Variable Rate Technology (VTR), which deposits the inputs at a precalculated optimal level at various locations in the farm, guided by GPS technology. The reduction of input application thus achieved has a positive economic and environmental impact. Precision agriculture reduces the carbon footprint of agriculture and lowers greenhouse gas emissions by saving the energy required to produce and apply these inputs (Balafoutis et. al. 2017). Developed countries are the most promising markets for the precision agriculture technology and the adoption of this technology in developing countries remains a challenge due to the cost factor (Griffin et. al. 2005; Mondal & Basu 2009). A significant impact of these technologies on achievement of the goals of sustainable intensification of crop production can only be realized when smallholder farmers, which own about 80% of the world's farmland, have access to them through incentives and subsidies.

Location-specific traditional knowledge

Location-specific indigenous knowledge is an important asset for people in developing and under-developed countries with limited access to agricultural technology and is an important resource for their livelihoods. Farmers in these countries have used this knowledge for thousands of years to produce food sustainably without the use of chemical inputs and farm machinery powered by fossil fuels. Approximately 90% of the world's 570 million farms are small (less than 10 ha), and most of them are located in rural areas of developing countries (Lowder et. al. 2016). Many of these farmers are poor and have limited access to technology, markets, and services, increasing the importance of traditional knowledge for productivity and economic viability of these farms. Further research and development to adapt these technologies to the current and future crop productivity and sustainability goals is needed. Some important traditional agricultural practices are discussed below

1. ***Agroforestry-*** It involves planting trees along with the crop to create a micro-climate that acts as a buffer to protect the crops against extremes of climate. The trees protect the farmland from soil erosion and the crop against extreme temperature, rain, and wind. At the same time, the farm produces a diversified range of products such as food, firewood, timber, and products of medicinal value. The system also helps to preserve biodiversity by providing habitat to multiple species of plants and animals Agroforestry is more common in low- and middle-income countries, particularly in tropical regions, but is gradually gaining ground in more temperate regions also (Jose et. al. 2012; Buck et. al. 1995). Increased recognition of Agroforestry as an effective conservation method is reflected in constantly increasing research and policy support (Wilson et. al. 2016).

2. ***Mixed Cropping-*** Mixed cropping or intercropping is a traditional system of agriculture in which the farmers cultivate two or more crops at one time on a farm. The main advantage of mixed cropping is reduction in the risk associated with a single crop failure, stability of outputs, resilience, and sustainability (Vandermeer, 1989). Mixed crop systems have also been found to reduce the losses associated with pests and diseases, suppress weed growth and reduce the requirement for inputs such as fertilizers and pesticides. Some common mixed cropping combinations are gains & pulses, and gains & oilseeds and right combinations can result in significant increase in yield. Mixed cropping systems are less dependent on external energy for stability due to the mutually beneficial and synergistic effect of different plant species and associated animal species (Hobbs & Morton, 1999). Studies have indicated that mixed cropping can reduce the incidence of diseases and pests (Kumar et. al. 2000; Rajvanshi et. al. 2002) and suppress weed growth (Hauggaard-Nielsen & Jensen 2001; Welsh et. al. 1999). The main economic advantage of multiple cropping system is that it offers economic stability as multiple products buffer the unexpected fluctuation in the price of one commodity. The disadvantage of multiple

cropping systems is that it may be more challenging to manage and may not always lead to higher yields. Also, it is more suitable for farms where seeds are sown manually.

3. ***Crop rotation:*** Crop rotation is the practice of growing different crops in successive seasons on a farm which improves soil fertility by increasing soil mineralization (Carpenter-Boggs et. al. 2000), and soil organic content (Adiku et. al. 2009, Sexton et. al. 2012, 2014). The practice also helps in achieving better control of weeds and pests (Beck 2003, Pederson & Lauer 2004, Karlen et. al. 1994) and results in increased yields (Yousaf 2016; Mannering & Griffith 1981; Peterson & Vavel 1981a&b). Food and Agricultural Organization (FAO) recognizes crop rotation as one of the most important methods of integrated Pest Management. It is also an effective tool for the interruption of disease cycles, as non-availability of the host plant species for a period of time interferes with the completion of pest life cycle and results in reduction in the inoculum present in the soil over time (Karlen, 1994). Various studies have reported that crop rotation can have a significant effect on soil microbial communities, which are influenced by the root's architecture and the chemical characteristics of root exudates (Lehman et. al. 2015, Benitez et. al. 2017). Soil microorganisms mediate 80-90% of all processes occurring in the soil (Nannipieri et. al. 2003) and a healthy microbial community favors plant growth and development. Soil microbes perform functions such as fixation of atmospheric nitrogen, release of plant growth regulators, production of antibiotics that inhibit the development of pathogenic microorganisms, improvement of soil texture by producing polymers, improve absorption of nutrients such as phosphorus and so on. Crop rotation is particularly important for organic farms which do not utilize chemical inputs for cultivation. The general principle of crop rotation is to plant a leguminous crop (e.g. pulses, alfalfa or clover) after a cereal crop (e.g. rice, wheat, maize) and then leave the farm undisturbed for at least one season. Many studies have shown that crop rotation can contribute significantly towards sustainability and long-term profitability without any requirement of additional investments (Stanger et. al. 2008, Sexton 2016).

4. ***Water Harvesting***- Rainwater harvesting is a practice of collecting and storing rainwater for productive use, instead of letting it run-off and cause soil-erosion and has

been practiced for millennia in most arid and semi-arid regions of the world (Oweis 2004). Agriculture uses 60-90% of available water in a region, and it is estimated that to meet the food requirement of growing population, a 53% increase in the consumption of water resources will be witnessed by 2050. This will be a huge burden on the already stressed water resources and the situation may worsen further by changing climatic patterns (Liu et. al. 2013, Singh et. al. 2014). Rainwater harvesting has been found to be a viable alternative for supplementing conventional water supplies for various purposes including crop irrigation and for minimizing the effects of droughts which may occur with increased frequency due to climate change (Ghimire et. al. 2015, Rockstrom 2015, Zheng et. al. 2019). Proper management of water used for agriculture and water-efficient irrigation practices can improve food productivity and also help mitigate the effect of climate change on agriculture (Yosef & Asmamaw 2015). Rainwater harvesting systems such as farm ponds, dams, and tanks can be an important source of water during water scarcity or irregular rainfall, and rainwater harvesting can prove to be an important factor in boosting farm productivity.

Conservation Agriculture

Conservation Agriculture (CA) is a resource-efficient and potentially sustainable farming system based on three guiding principles- 1) minimum soil disturbance, which means no-tillage or very little tillage, 2) maintenance of permanent soil cover and 3) crop system diversity by crop rotation. CA improves the natural biological processes occurring above and below the soil leading to improvement in water and nutrient uptake efficiency. The external inputs such as fertilizers, pesticides, weedicides, and mineral nutrients are introduced at the optimal level and in the manner and quantity in which biological processes are minimally disturbed (FAO 2012).

Agriculture contributes 10-12% to total anthropogenic greenhouse gas emissions, which was estimated to be 5.1-6.1 Gt CO2-eq/Yr in 2005 (Smith et. al. 2007). Conservation agriculture reduces greenhouse gas emissions by sequestering more carbon in the soil. The no-tillage/minimum tillage increases the amount of carbon in the soil by reducing the oxidation of organic material present in the soil, and also by locking carbon in the form of permanent soil cover. The no-tillage/minimum-tillage practice also reduces consumption of fuel for crop production, which not only increases farm profitability but also results in lower greenhouse gas emissions. The reduced agrochemical input also reduces the greenhouse gas emissions associated with nitrogen containing fertilizers. In fact, NO_2 released from the degradation of nitrogen-containing fertilizers is potentially about 300 times more effective than CO_2 in trapping heat (Cassia et. al. 2018).

The economic benefit from the reduced fuel usage and the lower labor cost associated with mechanized operations such as tillage and the external input application is proven; however, the benefit also depends on the type of crop and other growing conditions also. For example, under specific conditions, the practice of conservation agriculture can reduce mechanization cost up to more than 50% for maize and 75% for common wheat (Jensen 1990; McIsaac et. al. 1990). However, the overall economic benefit obtained from the adoption of conservation agriculture is determined by the production yield which is affected by many factors such as crop type, seed variety, soil conditions, pest management, and climate. In one study, an increase in gross margin of 6.6% was obtained by reducing production cost and maintaining the yield unchanged (Chetan et. al. 2016). Since conservation agriculture helps in increasing soil water holding capacity and achieving decreased evaporation from soil surface, the benefits are more evident in the arid and semi-arid regions (Rusinamhodzi et. al. 2011; Pittelkow et. al. 2015).

Yield improvements have been noted in several studies for different crops cultivated using conservation agriculture. Despite demonstrated sustainability and economic benefits from conservation agriculture, the adoption of this system of agriculture has been slow, mainly due to inconsistent results which may be attributed to the factors such as lack of experience of the farmer, slow increase in soil fertility, waterlogged soil following unexpected rains, use of fertilizers and other chemical inputs in inappropriate amounts, inefficient weed and pest management, diseases originating from the mulch and soil compaction etc (Farooq et. al. 2011; Linden et al. 2000).

The role of conservation agriculture in improving crop production sustainability has been reported by many studies. The no-till practice of conservation agriculture significantly reduces soil erosion. One study conducted on farms of Indiana, USA and reported in 1970 found that no-till methods reduced soil erosion by > 70% (Johnson & Moldenhauer 1979; . Similarly, the cultivation of tobacco with no-till method has been found to reduce soil erosion by > 90% (Wood & Worsham 1986). Application of fertilizers in no-till agriculture was found to significantly decrease the soil erosion due to water run-off (Chaves de Souza et. al. 2017). Thus, the practice of conservation agriculture can play an important role in preventing soil erosion and improving soil quality.

Availability of better seed planters for no-till soil and improved herbicides in many areas of the world in the past 40 years have contributed to wider adoption of CA. Currently, about 125 million hectares of land, or about 10 % of the overall agricultural land is under conservation agriculture. The maximum adoption rate is in Australia, Canada, and the southern cone of South America (above 50% of cropland), and adoption in African, Central Asian and Chinese countries is rising (Pisante et al., 2010; Friedrich et al., 2012). Greater acceptability and wider adoption of CA require cost-effective sources of good quality seeds, affordable mineral fertilizers, specialized equipment, and better pesticides.

Limitations associated with CA have been elaborated by (Shaxson et al., 2008) and can include increased crop diseases and insect pests (Cook, 2006), development of herbicide-tolerant weeds, over-reliance on agrochemicals, excess moisture, cooler soils, an initial increase in nutrient requirements, and the requirement for specialized nutrient management to avoid immobilization and volatilization (Malhi et al., 2011). When animals are included in the scheme, switching to CA is needed by a different method of tillage agriculture.

Crops and cultivars

The GR has made available to the farmers hybrid varieties of many staple crops such as wheat, rice and maize that has played an important role in increasing food production, alleviating hunger, and preventing the conversion of additional non-cultivated land for agricultural purposes (Evenson et. al. 2003). The substantial yield improvements of many crops played an important role in increasing the availability and affordability of the food products derived from these crops to the poorer section of the population. The increased productivity of crops brought about by the hybrid cultivars developed during the GR has also played an important role in alleviating poverty (Pretty 2008).

However, the GR has also led to some environmental and ecological problems such as widespread contamination of land and water resources with agrochemicals, soil erosion, loss of biodiversity due cultivation of high yielding varieties of a few crops and over-exploitation of water resources. The use of high-yielding hybrid varieties has also led to a significant increase in the carbon footprint of agriculture, mainly due to the use of fossil fuels in the production of agrochemicals and for mechanized operations (Foley et. al. 2005). It has been estimated that agriculture contributes between 10-14% of global anthropogenic greenhouse gas emissions (Francesco et. al. 2013)

With increasing population, stress on the natural resources and degradation of the environment, new agronomic practices will be required to feed the growing population sustainably. Development of new cultivars not only for the cereals and other staples but also for fruits and vegetables will be required. Plant breeding technologies and biotechnology is expected to play a major role in the achievement of this goal.

The past few decades have seen major progress in achievement of technological capabilities for developing new plant varieties with more control over the desired traits. These new breeding technologies can potentially meet the challenge of feeding an ever-growing population sustainably by increasing yields, which will not only help in sustainable intensification of agriculture but also help in the mitigation of the environmental and ecological problems caused by overuse of agrochemicals. Some plant breeding technologies and their present and future role in sustainable agriculture are discussed below.

1. ***Transgenic crops**:* The genes coding for desired trait in one species can be inserted into the genome of another species by using genetic engineering and the resulting organism is called a transgenic or genetically modified organism (GMO). The recombinant DNA technologies have allowed the precise introduction of a particular trait in plant species as opposed to the random outcomes of the traditional breeding. Also, the limitation of the

traditional breeding of transfer of traits only within the same species is bypassed using recombinant DNA technology and the traits from any species can be transferred to any other species. This is particularly useful for vegetatively propagating plants such as banana, sweet potato, and pineapple which are not amenable to improvement through conventional breeding. Currently, the most widely used GMOs are herbicide-tolerant and insect-resistant varieties of various crops (Kumar et. al. 2020). The use of transgenic crop has increase rapidly from 1.7 million hectare in 1996 to 191.7 million hectare in 2018, a 113 fold increase (ISAAA, 2018). The use of transgenic crops has played an important role in increasing crop yields by 22% and farmers' profits by 68% (Klümper & Qaim 2014).

2. ***Gene Editing****:* The technique of gene editing allows targeted modification of DNA of an organism by deletion, duplication, replacement, and modifications of bases. Unlike genetic engineering, which causes the insertion of genetic material randomly in the genome of an organism, the gene-editing techniques allow precise modifications at pre-determined sites. A number of nucleases such as meganucleases, zinc finger nucleases, transcription activator-like effector-based nucleases (TALENS), and CRISPER/Cas9 system are used for gene editing. The technology can be used for the generation of simple or complex mutations as well as for inter-specific gene transfers.

The earliest GMOs used in agriculture were insect-resistant crops, which contained bacterial genes from *Bacillus Thuringiensis*. Since then, various other crops such as cereals, sugar beet, soybean, corn, canola, papaya, and alfalfa etc. have been engineered with insect resistance, herbicide tolerance, virus resistance, and drought tolerance traits (ISAAA 2017). The pest and disease-resistant crops are expected to prove important for sustainable intensification of agriculture as their cultivation will minimize of losses due to pests and diseases and results in higher yields. Currently, many groups are working on the development of genetically modified crops such as maize, rice, wheat, beans, oilseeds etc., resistant to abiotic stress of heat, cold, salinity, and flooding (Kumar et. al. 2020). The crops with resistance to environmental extremes are important for mitigating the effect of climate change on agriculture. Work is also progressing in the direction of development of nutrient efficient crop varieties, which will reduce the amount of fertilizers required for optimal yields leading to a reduction in soil degradation and carbon footprint, an important step towards sustainability of agriculture. The researchers are also working on increasing the photosynthetic efficiency of plants for better yields (Simkin et. al. 2019). Success in these endeavors will be an important step towards sustainable food production and reduction in the conversion of additional non-agricultural land for cultivation.

Since the introduction of genetically modified Bt cotton, the genetically modified crops have found wide adoption in both developed and developing countries. The highest adoption rate is in North America, and South America followed by Asia. The acceptance of GMO crops in Europe and Asia has been poor because of unfavorable regulatory policies.

Weed and Pest control

Weeds cause formidable losses in agricultural production and are a major constraint in increasing agricultural yield. Even with current crop protection measures about one-third of the crop produced worldwide is lost to pests. The worldwide yield losses in three major crops, rice, wheat, and maize, due to weeds are estimated to be 27.3-33.7% of losses caused by all other pests together (Oerke 2006). Weed management is a significant part of the cost of production on farms. The availability of effective herbicides and herbicide-tolerant crops have reduced the cost associated with manual labor; however, the widespread use of herbicides is now causing environmental and ecological problems (Larson et. al. 19197; Arias-Estevez M et. al. 2008; Lopez-Flores et. al. 2003; Hijosa-Velsero et. al. 2016). The herbicides may directly affect the non-target organism by direct exposure or indirectly by causing changes to the ecosystem and food resources. For example, it has been found that the use of weedicide glyphosate has increased the level of pathogenic fungi in the soil by negatively affecting other micro-organisms that normally keep pathogenic fungi under check (Fernandez et. al. 2009; Kao et. al. 2019). In other studies, it was found that glyphosate could reduce the population of some earthworm species which helps in the maintenance of soil quality and fertility. (Santadino et. al. 2014). The application of glyphosate has also been found to disturb the population of some wildlife species around the fields where it is applied. For instance, glyphosate application has been linked to declining populations of Monarch butterflies since the mid-1990s in North America. The Monarch butterfly larvae feed primarily on the milkweed, and the use of glyphosate has resulted in a large reduction in the population of this plant (Pleasants & Oberhauser 2013). The glyphosate can be washed into the water reservoirs and also reach the underground aquifers by washing down the soil and rocks. The groundwater is a major source of drinking water in many areas.

Sustainable intensification of agriculture requires minimal use of chemical pesticides. Some conventional weed management methods such as the implementation of preventive measures, tillage and mechanical control, soil coverage, crop competition, crop rotation, and crop diversification etc. can be used along with biological and chemical control methods to effectively and sustainably manage weeds. The ecological concept of allelopathy can also be employed for weed control. With the increasing recognition of environmental, ecological, and human health problems caused by agrochemicals, it is important to adopt integrated weed management (IWM) system incorporating more than one method of weed control, which maximizes crop yield while reducing the impact on the environment and human health. For instance, integrating a dual culture of fish and Azolla has been found to effectively complement the weed control methods in rice (Cheng et. al. 2015). Off-season tilling and mulching of inter-row space in combination with herbicides can effectively manage weeds in cotton (Vijayabaskaran & Kathiresan 1993).

Herbivorous insects are responsible for about 20% crop loss globally despite an annual investment of about USD 40 billion in production and use of 3 million metric tonnes of pesticides and other non-chemical pest control methods (Agrawal 2011). The pesticide residue in the food and water resources poses serious health risks, and farms workers are at particularly high risk for developing health problems related to abnormally high pesticide exposures (Machado & Martins 2018). Pesticides also affect ecosystem stability by reducing insect biodiversity (Bengtsson et. al. 2005). There is an urgent need for pest management strategies which does not affect the yields but are environmentally and ecologically sustainable. Large-scale monocultures lead to increased prevalence of pests and diseases, whereas increased crop diversity achieved by crop rotation and intercropping can be beneficial in reducing pest and disease prevalence in agriculture. In one study, where cotton was interplanted with lucerne, a significant increase in predatory insects such as beetles, bugs, lacewings, and spiders was noticed in the fields. (Menash & Khan 2010). Another study in which castor was inter-cropped with cluster beans, chickpea, black gram, or groundnuts, a natural increase in the natural enemies (*Microplitis, coccinellids,* and spiders) of the major pests of castor was noticed. Not only the incidence and damage due to castor pests were minimized but also the inter-cropped systems were more efficient in terms of equivalent yields and equivalent land ratio (Rao et. al. 2012). Inter-cropping of tobacco and maize was found to reduce the tobacco brown spot leaf disease and simultaneously decrease the incidence of northern maize leaf blight by 19.7% (Li et. al. 2009), while in a maize-potato inter-cropping system, the severity of potato late blight was reduced by 39.4% (Li et. al. 2009). Thus, increasing crop diversity in the fields is an effective strategy to minimize the damage caused by pests and diseases. Another useful strategy for sustainable pest management is biological control, where natural enemies of the pests are used against them (Kenis et. al. 2017). The use of irradiated, sterile insects to stop the population growth of the pests has been used effectively against a number of pests (Klassen and Curtis, 2005). The behavior of a pest can also be used to control its population by use of baits, traps, and mating disruption. Microbial control (bacteria, fungi, viruses, and microsporidia) is another strategy that has also been used for sustainable pest control in many cases (Usta 2013).

An integrated pest and disease management system that combines different pest and disease control measures into an effective and sustainable solution adapted to local agricultural conditions is likely to be successful in controlling pests and diseases for more sustainable and intense agriculture.

Increasing efficiency of the post-production stage

Inefficiencies due to post-production wastage can put pressure on the agricultural system and affect its sustainability. Thus, proper planning and availability of infrastructure and policies at the supply chain and consumption levels are required. For example, lack of appropriate storage facilities for produced food or lack of facilities for timely transport to areas of consumption may lead to loss of food to pests and spoilage. In fact, 30-40% of food in both developed and developing world is lost due to wastage, though the causes behind this are very different in the developing and the developed countries (Nellemann et. al. 2009; Stuart 2009) . The food is also wasted at the consumer level; for example, in developed countries, the consumer preference for food of a certain cosmetic standard leads to rejection and wastage of perfectly edible but visually less appealing products. In many cases, the existing legislation forces the retailers to discard the products by their 'use by' dates, though they may still be good for consumption. These problems are more difficult to tackle as these are dependent on human behavior, which is more difficult to change. Awareness programs on the magnitude of problem of food wastage and re-examination of the legislature for 'use by' or 'sell by' dates among other measures, may help in tackling the problem of food wastage at this level. Thus, sustainable food production not only depends on the food growing capabilities but also on the available means to prevent the spoilage and wastage of the produced food.

Conclusion

The growing population and the simultaneous degradation of natural resources and ecosystem services due to current chemical-intensive agricultural systems have necessitated the adoption of new farming practices that do not compromise on the yield but at the same time are more considerate to the environment. Multi-stakeholder innovation processes play a significant role in generating workable, practical solutions that farmers will be motivated to accept and adopt. The traditional knowledge of farmers, which includes many elements of sustainable agriculture, can be merged with the modern scientific understanding of sustainable systems to create effective solutions for sustainable intensification of agriculture. The chemical inputs used in industrial agriculture can still be used but within a broader framework of a sustainable system where their use is minimized in favor of more environmental friendly options. Innovative and sustained efforts to reduce the wastage of food are also required to reduce the burden on agricultural systems.

References

Adiku SGK, Jones, JW, Kumaga FK and Tonyigah A, 2009. Effects of crop rotation and fallow residue management on maize growth, yield and soil carbon in a savannah-forest transition zone of Ghana. *J. Agricultural Science*, 147:313-322.

Agrawal A, 2011. Evolutionary ecology of plant defences: current trends in evolutionary ecology of plant defence. *Funct. Ecol.*, 25:420–432.

Alston J, 2010. The benefits from agricultural research and development, innovation, and productivity growth. OECD Food, agriculture and fisheries working papers, No.31.

Arias-Estevez M, Lopez-Periago E, Martinez-Carballo E, Simal-Gandara J, Mejuto JC, Garcia-Rio L, 2008. The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agric. Ecosyst. Environ.* 123:247–260.

Badgley C, Moghtader J, Quintero E, Zakem E, Chappell M, AvilesVazquez K, Samulon A, Perfecto I, 2007. Organic agriculture and the global food supply. *Renew. Agr. Food Syst.* 22:86-108.

Balafoutis A, Beck B, Fountas S, Vangeyte J, Van der Wal T, Soto I, Gomez-Berbero M, Barnes A, Eory V, 2017. Pecision agriculture technologies positively contributing to GHG emissions, mitigation, farm productivity and economics. Sustainability. 9: 1339-67.

Balmford A, Green RE, Scharlemann JPW, 2005. *Global Change Biol.* 11:1594-601.

Bavel JV 2013. The world population explosion: causes, backgrounds and projections for the future. Facts Views Vis ObGyn, 5(4):281-291.

Beck DL, 2003. Profitable No-Till Systems Designed for Producers in the North American Great Plains and Prairies. Conference Proceedings, 2003, 6th Annual Northwest Direct Seed Cropping Systems Conference. Pasco, WA. (14).

Benitez S, Shannon, LO, Michael LR, 2017. Effects on maize seedling health and associated rhizosphere microbiome. Scientific Reports. 7:15709 DOI: 10.1038/s41598-017- 15955-9 1. (On line 16 November2017).

Bengtsson J, Ahnström J, Weibull AC, 2005. The effects of organic farming on biodiversity and abundance: a meta-analysis. *J. Appl. Ecol.*, **42:**261–269.

Bruinsma, J. 2009. The resource outlook to 2050: By how much do land, water use and crop yields need to increase by 2050? 33 pp. Expert Meeting on How to Feed the World in 2050. Rome, FAO and ESDD. (Available at: ftp://ftp.fao.org/docrep/fao/012/ak542e/ak542e06.pdf).

Buck L, 1995. Forestry policy issues and eseach diections in the US and less developed counties: Insights and challenges from ecent experience. *Agroforestry Systems*. 30: 57-53.

Carpenter-Boggs L, Reganold JP and Kennedy AC, 2000. Effects of biodynamic preparations on compost development. *Biol. Agric. Hort.* 17(4):313-328.

Cassia R, Nociono M, Correa-Aragunde N, Lamaltina L, 2018. Climate change and the impact of greenhouse gases: CO2 and NO, friends and foes of plant oxidative stress. *Front. Plant. Sci.* 9:273.

Chaves de Souza V.F., Bertol I., Wolschik H, 2017. Effect of soil management practices on water erosion under natural rainfall conditionson humid dystrudept. *Rev. Bras. Cienc. Solo.* 2017;41:e0160443.

Cheng W, Okamoto Y, Tawaraya K, Takie M, Yasuda H, 2015. Combined use of Azolla and loach suppressed weed *Monochoria Vaginalis* and increased rice yields without agrochemicals. *Organic Agriculture*, 5(1):1-10.

Chetan F, Rusu T, Chetan C, Moraru PI, 2016. Influence of soil tillage upon weeds, production and economic efficiency of corn crop. *Agro Life Sci. J.* 5:36–43.

Conway G, 2012. One Billion Hungry: Can we feed the world. Cornel University Press: Ithaca,NY, USA.

Cook RJ, 2006. Towards cropping systems that enhance productivity and sustainability *Proc. Natl. Acad. Sci. USA* 103(49):18389-18394.

de Derecho Ambiental, CM, 2003. The Economic and Environmental Impacts of Agricultural Subsidies: A Look at Mexico and Other OECD Countries; Unisféra International Centre: Unisféra, QC, Canada, 2003.

Derksen DA, Anderson RL, Blackshaw RE, Maxwell B, 2002. Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agron. J.* 94:174-85.

Evenson E, Gollin D, Evenson RE, Rosegrant M, 2003. in Crop Variety Improvement and its Effect on Productivity, eds. Evenson RE, Gollin D (CABI, Wallingford, UK) 473-479.

FAO, 2004. The State of Food and Agriculture 2003-2004 (Food and Agricultural organization of the United Nations, Rome).

FAO, 2009. High Level Expert Forum: How to feed the world in 2050. Rome 12-13 Oct. http://www.fao.org/fileadmin/user_upload/lon/HLEF2050_Global_Agriculture.pdf.

FAO, 2012. Conservation Agriculture. http://www.fao.org/ag/ca/6c.html.

FAOSTAT, *http://faostat.fao.org/default.aspx* (2009).

Fargione F, Hill J, Tilman D, Polasky S, Hawthorne P, 2008. Land clearing and the biofuel carbon debt. Science 319:1235-8. Friedrich T, Derpsch R, Kassam AH, 2012. Global overview of the spread of Conservation Agriculture. FACTS Reports 6:1-8.

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM, 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil. Tillage. Res.* 117:172–183.

Fernandez MR, Zentner RP, Basnyat P, Gehl D, Selles F, Huber D, 2009. Glyphosate associations with cereal diseases caused by *Fusarium* spp. in the Canadian Prairies. *Eur J Agron.*, 31:133–143.

Foley et. al., 2005. Global consequences of land use. *Science,* 309(5734): 570-574.

Food and Agriculture Organization of the United Nations (FAO), State of Food Insecurity in the World 2009 (FAO, Rome, 2009).

Francesco NT, Mirella, S, Simone R, Alessandro F, Nuala F, Pete S, 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ. Res. Lett.* 8: 015009.

Friedrich T, Derpsch R, Kassam A. 2012. Overview of the global spread of conservation agriculture. *Field Actions Science Reports.* Special issue 6:1-7.

Frison E, 2008. Biodiversity: Indispensable resources. *Dev. and Cooperation.* 49(5):190–93.

Ghimire SR, Johnston JM, 2015. Traditional knowledge of rainwater harvesting compared to five modern case studies World Environmental and Water Resources Congress 2015. 182–193.

Godfray HCJ, Beddington J, Crute IR, Haddad L, D Muir JF, Lawence, Pretty J, Robinson S, Thomas SM, Toulmin C, 2010. Food Security: The challenge of feeding 9 billion people. *Science* 327(5979): 812-818.

Griffin T, Lowenberg-DeBoer J, 2005. Worldwide adoption and profitability of precision agriculture: Implications for Brazil. *Rev. Polít. Agríc.* **14**(4):20–38.

Hauggaard-Nielsen H, Ambus P, Jensen ES, 2001. Interspecific competition, N use and interference with weeds in pea-barley intercropping, *Field Crop. Res.* 70:101–109.

Hijosa-Valsero M, Bécares E, Fernández-Aláez C, Fernández-Aláez M, Mayo R, José Jiménez J, 2016. Chemical pollution in inland shallow lakes in the Mediterranean region (NW Spain): PAHs, insecticides and herbicides in water and sediments. *Sci. Tot. Environ.,* 544:797–810.

Hobbs RJ, 1989. The nature and effects of disturbance relative to invasions. Pages 389-405 in Drake JA, Mooney HA, di Castri F, Groves RH, Kruger FJ, Rejmanek M, and Williamson M, editors. Biological invasions. A global perspective. Wiley, Chichester, England.

IPCC, 2007. Fresh water resources and their management: Climate Change 2007; Impact, adaptation and vulnerability. Contribution of working group-II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press: Cambridge, UK.

ISAAA, 2017. Global Status of Commercialized Biotech/GM Crops in 2017: Biotech Crop Adoption Surges as Economic Benefits Accumulate in 22 Years. *ISAAA* Brief No. 53. ISAAA: Ithaca, NY.

ISAAA, 2018. Global Status of Commercialized Biotech/GM Crops in 2018: Biotech Crops Continue to Help Meet the Challenges of Increased Population and Climate Change. *ISAAA,* Brief No. 54. ISAAA: Ithaca, NY.

Johnson CB, Moldenhauer WC, 1979. Effect of Chisel versus moldboard plowing on soil erosion by water. *Soil Sci. Soc. Am. J.* 43: 177-179.

Jensen PK, 2019. Use of integrated weed management tools in crop rotations with grass seed production. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 69:209–218.

Jose S, 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry Systems*, 76:1–10.

Joseph C, 2020. Wold population 2020 overview. Yale Global Online 2020. (Available at https://yaleglobal.yale.edu/content/world-population-2020-overview).

Kao HY, Chung KR, Huang JW, 2019. Paraquat and glyphosate increase severity of strawberry anthracnose caused by *Colletotrichum gloeosporioides. J. Gen. Plant Path.*, 85:23-32.

Kassam AH, Friedrich T, Rolf Derpsch R, Lahmar R, Mrabet R, Basch B, Emilio J, González-Sánchez EJ, Serraj R, 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crop Res*, 132:7-17.

Karlen DL, Varvel GE, Bullock DG, Cruse RM, 1994. Crop rotations for the 21st century. *Adv. Agron.* 53:1-44.

Kenis M, Hurley BP, Hejek AE, Cock MJW, 2017. Classical biological control of insect pests of trees: facts and figures. *Biological Invasions,* 19:3401-3417.

Klassen W, Curtis CF, 2005. History of the sterile insect technique, pp. 3-36 In V. A. Dyck, J. Hendrichs, and A. S. Robinson. The Sterile Insect Technique: Principles and Practice in Area-Wide Integrated Pest Management. Springer, Dordrecht, The Netherlands. 787 pp.

Klümper W, Qaim M, 2014. A Meta-Analysis of the Impacts of Genetically Modified Crops. *PLoS ONE* 9:e111629.

Kumar A, Solanki KR, Singh R, 2000. Effect of Wheat as intercrop on incidence of powdery mildew of ber (Zizyphus mauritiana), *FACTRR* 4:121–124.

Kumar K, Gambhir G, Dass A, Tripathi AK, Singh A, Jha AK, Yadava P, Chaudhary M, Rakshit S, 2020. Genetically modified crops: Current status and future prospects. *Planta*, 251:91.

Larson SJ, Capel PD, Majewski MS, 1997. Pesticides in surface waters—distribution, trends, and governing factors. In: Series of Pesticides in Hydrologic System. Gilliom RJ (ed.). Ann Arbor Press, Chelsea, Michigan.

Landers J, 2007. Tropical crop-livestock systems in conservation agriculture: the Brazilian experience. Integrated Crop Management, Vol. 5., FAO, Roma, Italy.

Latruffe L, 2010. Competitiveness, productivity and efficiency in the agricultural and agri-food sectors. OECD Food, agriculture and fisheries working papers, No.30. OECD Publ., Paris, France.

Lehman RM et al. (2015) Understanding and enhancing soil biological health: The solution for reversing soil degradation. *Sustainability*, 7:988-1027.

Li et. al., 2009. Crop diversity for yield increase. *PLoS ONE*, Nov. 26. https://doi.org/10.1371/journal.pone.0008049.

Liang L, Wang Y, Ridoutt BG, Lal R, Wang D, Wu W, Wang L, Zhao G, 209. Agricultural subsidies assessment of cropping systemsfrom environmental and economic perspective in Noth China based on LCA. *Ecol. Indic.* 96: 351-60.

Linden DR, Clapp CE, Dowdy RH, 2000. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. *Soil Tillage Res.* 56:167–174.

Liu J, Folberth C, Yang H, Rockstrom J, Abbaspour K, Zehnder AJB, 2013. A global and spatially explicit assessment of climate changeimpacts on crop production and consumptive water use. *PLoS ONE*. Https://doi.org/10.1371/journal.pone.0057750.

López-Flores R., Quintana XD, Salvadó V, Hidalgo M, Sala L, Moreno-Amich R: Comparison of nutrient and contaminant fluxes in two areas with different hydrological regimes (Empordà Wetlands, NE Spain). *Water Res.* 37:3034–3046.

Lowder S, Skoet J, Raney T, 2016. The number, size and distribution of farms, smallholder farms and family farms worldwide. *World Development.* 87:16–29.

Machado SC, Martins I, 2018. Risk assessment of occupational pesticide exposure: use of endpoints and surrogates. *Regul. Toxicol. Pharmacol.,* 98:276–283.

Malhi SS, Nyborg M, Goddard T, Puurveen D, 2011a. Long-term tillage, straw and N rate effects on some chemical properties in two contrasting soil types in Western Canada. *Nutr. Cycling Agro ecosyst.* 90: 133-146.

Mannering JV, Griffith, DR, 1981. Value of crop rotation under various tillage systems. *Agron. Guide AY-230. Coop. Ext. Serv.* Purdue Univ.,West Lafayette, IN.

McIsaac GF, Siemens JC, Hummel JW, Tyrrell AT, 1990. Economic comparison of six corn and soybean tillage systems, two soybean rows spacing on three farm sizes. *Appl. Eng. Agric.* 6:557–564.

Menash R, Khan M, 2010. Use og Medicago Sativa (L.) interplantings/trap crops in the mangement of green mirid, Criontiades dilutes (Stal) in commercial cotton in Australia. *Int. J. Pest Manag.*, 43(3):197-202.

Mondal P, Basu M. 2009. Adoption of precision agriculture technologies in India and in some developing countries: scope, present status and strategies. *Prog. Nat. Sci.* 19(6):659–66.

Nannipieri P, Asche-Jenull J, Ceccherini MT, 2003. Microbial divesity and soil functions. *Eur. J. of Soli Sci.* 54:655-70.

Nellemann C *et. al*., Eds., The Environmental Food Crisis. [United Nations Environment Programme (UNEP), Nairobi, Kenya, 2009].

Oerke EC, 2006. Crop losses to pests. *J. Agric. Sci.,* 144(01):31-43.

Oweis T, Hachum A, Bruggeman A, (eds), 2004. Indigenous Water Harvesting Systems in West Asia and North Africa. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Pedersen P, and Lauer JG, 2004. Soybean growth and development response to rotation sequence and tillage system. *Agronomy Journal* 96:1005-1012.

Peterson TA, Varvel GE, 1989a. Crop yield as affected by rotation and nitrogen rate. I. Soybean. *Agronomy Journal.* 81:727-731.

Peterson TA and Varvel GE, 1989b. Crop yield as affected by rotation and nitrogen rate. II. Sorghum. *Agronomy Journal.* 81:731-734

Pisante M, Corsi S, Amir K, Friedrich T, 2010. The challenge of agricultural sustainability for Asia and Europe. TSR 17:662-7.

Pittelkow CM, Liang X, Linquist BA, van Groenigen KJ, Lee J, Lundy ME, van Gestel N, Six J, Venterea RT, van Kessel C, 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature.* 517:365–368.

Pleasants J,M, Oberhauser KS, 2013. Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. *Insect Conserv. Div.,* 6, 135–144.

Porter ME, Ketels C, Delgado M, 2007. The microeconomic foundations of prosperity: findings from the business. The global competitiveness report 2007-2008. World Economic Forum.

Pretty J, 2008. Agricultural sustainability: Concepts, principles and evidence. *Philos. Trans. R. Soc. B* 363:447-465.

Rajvanshi I, Mathur BN, Sharma GL, 2002. Effect of intercropping on incidence of Heterodera avenae in wheat and barley crops. *Annu. Plant Protection Sci.* 10:365–410.

Rao MS, Rao CR, Srinivas K, Pratibha G, Sekhar SM, Vani GS, 2012. Intercropping for management of insect pests of castor, *Ricinus communis*, in the semi–arid tropics of India. *J. Insect Sci.*, 12:1536-2442.

Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA, 2012. Recent patterns of crop yield growth and stagnation. *Nat. Commun.*.1-19.

Rockstrom J, Falkenmark M, 2015. Agriculture: Increase water harvesting in Africa. *Nature*, 519(7643): 283-285.

Royal Society of London, 2009. Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture.

Rusinamhodzi L, Corbeels M, van Wijk MT, Rufino MC, Nyamangara J, Giller KE, 2011. A meta-analysis of long-term effects of conservation agricolture on maize grain yield under rain-fed condition. *Agron. Sustain. Dev.* 31:657–673.

Santadino M, Coviella C, Momo F, 2014. Glyphosate sublethal effects on the population dynamics of the earthworm *Eisenia fetida* (Savigny, 1826). *Water Air Soil Pollut.*, 225:2207.

Sexton P, Berg R, Beck D, 2012. Effect of cover crops on corn N requirements in a drought year. South Dakota State University Agricultural Experiment Station. Southeast Research Farm Annual Progress Report. 21-25.

Sexton, P, Johnson D, and Rops B, 2014. Evaluation of effects of cover crops on corn N requirements 2014. South Dakota State University Agricultural Experiment Station. Southeast Research Farm Annual Progress Report. 30-32.

Sexton P, 2016. Chapter 9: Crop rotations can increase corn profitability and reduce pests. In: "iGrow Corn: Best Management Practices", Clay, D.E., C.G. Carlson, S.A. Clay and E. Byamukama (Ed.). South Dakota State University.

Shaxson F, Kassam AH, Friedrich T, Boddey B, Adekunle A, 2008. Underpinning the benefits of conservation agriculture: sustaining the fundamental of soil health and function. Main document for the workshop on investing in sustainable crop intensification: The case of soil health, 24-27 July, FAO, Rome, Italy.

Shockley JM, Dillon CR, Stombaugh, T, 2011. A whole farm analysis of the influence of auto-steer navigation on net returns, risk and production practices. *J. Agric. Appl, Econ. 43*(1), 57–75.

Shockley JM, Dillon, CR, Stombaugh T, Shearer S, 2012. Whole farm analysis of automatic section control for agricultural machinery. *Precision Agriculture, 13*(4), 411–420.

Simkin AJ, Lopez-Calcagno PE, Raines CA, 2019. Feeding the world: Improving photosynthetic efficiency for sustainable crop production. *J. Exp. Bot.,* 70(4): 1119-1140.

Singh VP, Mishra A, Chowdhary H, Khedun CP, 2014. Climate change and its impact on water resources. Handbook of Environmental Engineering, vol. 15, Modern Water Resources Engineering. Springer Science+Business Media, New York.

Smith P. etl al. [Agriculture] Climate Chnage 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz B. et. al. (ed.)] (Cambridge University Press, Cambridge, United Kingdom & New York, 2007.

Stanger TF, JG Lauer, Chavas JP, 2008. The profitability and risk of long term featuring different rotations and nitrogen rates., cropping systems, *Agronomy Journal.* 100(1): 105-113.

Stombaugh TS, McLaren, D, & Koostra B, 2005. The global positioning system. Lexington: University of Kentucky Cooperative Extension Service. (Technical Bulletin No. AEN-88).

Stuart T, 2009. Uncovering the Global Food Scandal. (Penguin, London).

Usta C, 2013. Microorganisms in Biological Pest Control — A Review (Bacterial Toxin Application and Effect of Environmental Factors), Current Progress in Biological Research, Marina Silva-Opps, IntechOpen, DOI: 10.5772/55786. Available from: https://www.intechopen.com/books/current-progress-in-biological-research/microorganisms-in-biological-pest-control-a-review-bacterial-toxin-application-and-effect-of-environ

Vandermeer J.H. (1989) The Ecology of Intercropping, Cambridge University Press, Cambridge, UK.

Vijayabaskaran S and Kathiresan RM, 1993. Integrated weed management in rice-cotton cropping system. Proceedings of the international symposium on integrated weed management for sustainable agriculture, November 18–20, Hisar, India, pp: 62.

Walter A, Finger R, Huber R, Buchmann N, 2017. Opinion: Samrt farming is key to sustainable agriculture. *PNAS*, 114(24):6148-6150.

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Welsh JP, Philipps L, Bulson HAJ, Wolfe M, 1999. Weed control for organic cereal crops. Proceedings of the Brighton Crop Protection Conference – Weeds, Brighton, UK, 945–950.

Wik M, Pingali P, Broca S, 2008. Background Paper for the World Development Report 2008: Global Agricultural Performance: Past Trends and Future Prospects (World Bank, Washington, DC).

Wilson, Matthew & Lovell, Sarah. (2016). Agroforestry—The Next Step in Sustainable and Resilient Agriculture. *Sustainability.* 8:574.

Wood SD, Worsham AD, 1986. Reducing soil erosion in tobacco fields with no-tillage transplanting. *Soil Water Conserv.* 51:193-196.

World Bank. World Development Report 2008: Agriculture for Development (World Bank, Washington, DC, 2008).

World Health Organization fact sheet, 2020. https://www.who.int/news-room/fact-sheets/detail/malnutrition

Yosef BA, Asmamaw DK, 2015. Rainwater harvesting: An option for dry land agricultue in arid and semi-arid Ethiopia. *Int. J. Water Res. Environ. eng.* 7(2):17-28.

Yousaf M, Li X., Zhang Z, Ren T, Cong R, Ata-Ul-Karim ST, Fahad S, Shah AN, Lu J, 2016. Nitrogen fertilizer management for enhancing crop productivity and nitrogen use efficiency in a rice-oilseed rape rotation system in China. *Front Plant Sci.* 7

Zhang S, Zhang J, Yue T, Jing X, 2019. Impacts of climate change on urban rainwater harvesting systems. *Sci Total Environ.* 15(665): 262-274.