4 Future Smart Crops for paddy fallow agri-food systems in Southeast Asia

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4.1 Achieving global food security

Food security, as defined by the United Nations' Committee on World Food Security, is the condition in which all people, at all times, have physical, social and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Over the coming decades, a changing climate, growing global population, increasing incomes, changes in food choices, rising food prices, and environmental stressors, such as increased water scarcity and land degradation, will have significant yet uncertain impacts on food security. There are different aspects having direct links to meeting food security at the global level, including globalization of markets.

4.1.1 Growing food demand

Ensuring global food security for the ever-growing population, which will reach over nine billion by 2050, and reducing poverty is a challenging task. Growing per capita incomes in emerging economies such as Brazil, China, India and Russia imply additional pressure on global food production due to changing food habits. Increased food production has to come from the available and finite water and land resources that are declining in quality (Wani *et al.*, 2011a) The amounts of available water and land have not increased since 1950, but the availability of water and land per capita has declined significantly with the increase in the global human population. For example, in India, the per capita water availability has declined from 5 177 m^3 in 1951 to 1 820 m^3 in 2001, with the population increasing from 361 million in 1951 to 1.02 billion in 2001. India's population is expected to rise to 1.39 billion by 2025 and to 1.64 billion by 2050, with associated reductions in per capita water availability of 1 341 m^3 by 2025 and 1 140 m^3 by 2050. The distribution of water and land varies between countries and regions, as do the current population and anticipated growth, which is likely to be more in developing countries. In 2009, more than one billion people were undernourished, not due to food shortages (availability), but to poverty (accessibility). While the percentage of hungry people in the developing world has been dropping for decades, the absolute number of hungry people worldwide has barely changed.

4.1.2 Limited fresh water resources

Water is the most common natural resource on Earth and covers 70 percent of its surface, However, 97.25 percent is salt water found in the oceans, while 2.75 percent is freshwater found in the icecaps, glaciers, groundwater, lakes, rivers and the atmosphere (Postel, Daily and Ehlich., 1996; Rockström, Gordon and Folke, 1999). Less than 1 percent of the Earth's water is considered available as freshwater. Water circulation in the hydrological cycle of evaporation, transpiration and precipitation is mainly driven by various climatic and land management factors (Falkenmark, 1997). Rockström, Gordon and Folke (1999) reported that about 35 percent of annual precipitation (110 305 km^3) returns to the ocean as surface runoff (38 230 km^3) while the remaining 65 percent is converted into water vapour flow. Moreover, major terrestrial biomes – forest, woodlands, wetlands, grasslands and croplands – consume approximately 98 percent of global green water flow and generate essential ecosystem services (Rockström, Gordon and Folke, 1999, Rockström and Gordon, 2001). With the increasing population pressure, the availability of freshwater for food production is a concern. An estimated 6 700 and 15 100 $km^3\ y^{-1}$ of freshwater is used by croplands and grasslands, respectively, to generate food and animal protein for human consumption, This quantity is 30 percent of total green water flux on the Earth (Rockström and Gordon, 2001).

4.1.3 Challenges and opportunities of water management in rain-fed agriculture

Water is the primary limiting factor in dryland agriculture (Falkenmark, *et al*.. 2008). Rainfall in dryland areas is characterized by an erratic and non-uniform distribution that results in frequent dry spells during the monsoon. A study (Barron, Rockström, Gichuki J. *et al*.) in 2003 looked at dry-spell occurrence in semi-arid locations in Kenya and Tanzania; where 70 percent of dry spells lasting longer than ten days occurred during the water-sensitive flowering stage of the crop (maize). In the semi-arid Nandavaram watershed, Andhra Pradesh, India, with approximately 650 mm of annual rainfall, there is a greater than 40 percent risk of dry-spell occurrence during vegetative and flowering stages of the crop, while in the semi-arid Xiaoxingcun watershed in Yunan province in southern China, with similar rainfall, there is only a 20 percent risk of early-season dry spells (Rao, *et al*., 2010).

To achieve better crop growth and yield, a certain amount of water is required to meet plant metabolic and evaporative demands (Stewart, 1977). A direct relationship exists between consumptive evapotranspiration (ET) water use and crop growth/yield. Rockström, Hatibu and Oweis (2007) explained that if all the green water captured in the root zone is utilized fully by the crop, yields of 3 tonnes per hectare are achievable in rain-fed agriculture. If the water is lost to deep percolation and surface runoff, then crop production levels would reach 5 tonnes per hectare and perhaps up to 7.5 tonnes per hectare, assuming that plant nutrient availability is non-limiting. In reality, only a small fraction of rainfall is used by plants (through transpiration), and the rest is channelled into non-productive use or lost as evaporation. Water stress, particularly during critical growth stages, reduces crop yield and may even damage the entire crop. Extensive data from productivity enhancement studies in Africa and Asia demonstrate the enormous potential to enhance green water-use efficiency as well as increase the availability of green water (Wani Pathak and Tam, 2002; Wani, Pathak and Jangawad, 2003; Wani, Joshi and Raju, 2008; Wani, Sreedevi and Marimuthu, 2009b; Wani, and Rockström, 2011c; Rockström, Hatibu and Oweis, 2007; Barron and Keys, 2011).

Green water management in rain-fed agriculture is of the utmost importance for enhancing water-use efficiency. Of the 1 338 million poor people worldwide, most live in the developing countries of Asia and Africa in dryland/rain-fed areas (Rockström, *et al*., 2007; Wani, et al., 2009a and 2011b; Anantha and Wani, 2016). Approximately 50 percent of the total global land area is in dry and arid regions (Karlberg, Rockström and Shiklomanov, 2009). The reliance on rainfed agriculture varies regionally. In sub-Saharan Africa, more than 95 percent of the farmed land is rain fed, with almost 90 percent in Latin America, 60 percent in South Asia, 65 percent in East Asia, and 75 percent in the Near East and North Africa (FAOSTAT, 2010). A large proportion of the global expansion of cropland areas since 1900 has occurred in rain-fed regions. Native vegetation, such as forests and woodlands, were converted into croplands and grasslands to produce more staple foods and animal protein. This has led to severe land degradation, depletion of soil nutrients and loss of biodiversity, which resulted in poor productivity and a loss of system resilience and ecosystem services (Gordon *et al*., 2005.). Most countries depend on rain-fed agriculture for grain food production. In many developing countries, a significant number of poor families face poverty, hunger, food insecurity and malnutrition, which intensify with adverse biophysical growing conditions and poor socio-economic infrastructure (Wani, *et al*., 2011a). In other words, where water limits crop production, poverty is strongly linked to variations in rainfall and to the farmers' ability to bridge intra-seasonal dry spells (Karlberg Rockström and Shiklomanov, 2009).

4.1.4 Climate-change impact

Climate change is one of the major challenges faced by agriculture worldwide. Crop production, which is vital to global food security, is being affected by climate change, more so in impoverished communities. It has been predicted that over the next decades, billions of people, especially those living in developing countries, will face water and food shortages, and greater risks to health and life because of climate change. With fewer social, technological and financial resources for adapting to changing conditions, developing countries are the most vulnerable to the impacts of climate change (UNFCCC, 2007). Although some crops may benefit, the overall impacts of climate change on agriculture are expected to be negative (IFPRI, 2009).

With climate change, temperatures are increasing, and rainfall variability is expected to increase further. A decrease in rainfall coupled with higher atmospheric requirements due to elevated temperatures is likely to shorten the rain-fed crop-growing period. A study carried out by ICRISAT on climate change revealed a net reduction in the dry sub-humid area in India (10.7 million ha) between 1971-1990 and 1991-2004, indicating that moderate climates are shifting towards both drier and wetter types. Similarly, a recent study by ICRISAT revealed that maize and sorghum yields in the

Nalgonda district (Telangana state) and Parbhani district (Maharashtra state) in India have declined in the last few years due to rising temperatures (Kumara, Moses, Bantialn *et al*., 2016). The length of the growing period has decreased by 15 days in Nalgonda district, leading to crop moisture stress and ultimately reduced yields (Rao and Wani, 2010). Simulation studies using the Decision Support System for Agricultural Technologies (DSSAT) predicted that the estimated 3.3°C temperature increase expected by the end of this century would, on average, reduce crop yields by 27 percent in the Parbhani district, Maharashtra state (Wani *et al*., 2009a).

Even though the exact nature and extent of climate change remain uncertain, it is widely believed that it is the poor who will be hit hard. With undesirable climatic conditions, such as droughts and floods increasing the risk of crop losses, an approach is needed to educate farmers on the impact of climatic variation. Crop success or failure is dependent on the prevailing environmental factors, and the mechanisms for managing environmental stress continue to be the subject of extensive studies in a variety of disciplines. Crop production is increasingly vulnerable to the risks associated with climatic change, including more extreme weather events, such as heavy precipitation, higher coastal waters, geographic shifts in storm and drought patterns, and warmer temperatures (IPCC, 2012).

Climate change is expected to cause substantial crop reductions in South Asia (up to 10 percent for staples, such as paddy, and greater than 10 percent for millet and maize) and in southern Africa (up to 30 percent for maize) by 2030 (Lobell *et al*., 2008). In the mid to high latitudes, crop productivity may increase slightly with a 1-3°C increase in local mean temperatures. At lower latitudes, crop productivity will decrease even with a relatively minor change in temperature (IPCC, 2007). Localized extreme events and sudden pest and disease outbreaks are already causing greater unpredictability in production from season-to-season and year-to-year, and require rapid and adaptable management responses (FAO-PAR, 2011). By 2050, it is predicted that the global population will be more than 9 billion people, increasing the demand for food and other agricultural products. At the same time, the world faces challenges including land and water scarcity, increased urbanization, and climate change and volatility. Agricultural production remains the main source of income for most rural communities (about 86 percent of the rural population or 2.5 billion people). Improving the adaptability of crops to the adverse effects of climate change is imperative for protecting and improving the livelihoods of the poor and ensuring food security (FAO, 2012). According to the Consultative Group on International Agriculture Research (CGIAR), one third of all human-caused greenhouse gas emissions come from our food system (Thornton, 2012). Climate-change adaptation requires more than simply maintaining the current levels of performance of the agricultural sector; it requires developing a set of robust yet flexible responses that will improve the sector's performance even under the changing conditions brought about by climate change.

Efforts should include the promotion of a holistic, integrated approach to harness the full potential of existing resources by increasing efficiencies and integrating all available resources. Such a holistic approach should focus on

- conserving and utilizing natural endowments, such as land, water, plant, animal and human resources, in a harmonious and integrated manner with low-cost, simple, effective and replicable technology; and
- minimizing the inequalities between irrigated and rain-fed areas, and poverty alleviation.

This approach aims to improve the standard of living through an increased earning capacity, and by making available the facilities required for optimum production and disposal of marketable surplus (Wani, Ramakrishna and Sreedevi, 2006). This approach should include the adoption of land- and water-conservation practices, water harvesting in ponds and recharging of groundwater to increase the potential of water resources, an emphasis on crop diversification, use of improved varieties of seeds, integrated nutrient management, and integrated pest management practices.

In the following section of this chapter, we focus on strategies to increase the productivity of rice-based cropping systems by bringing vertical integration into the existing cropping system in Southeast Asian countries to meet the increasing food demand. We analyse the current status of paddy fallows in Cambodia, Indonesia, Lao PDR, Myanmar and Thailand, and assess the potential for intensifying cropping systems. Based on this analysis, we propose a new paradigm for enhancing agricultural productivity per unit area through the introduction of more adaptable crops with a holistic management approach. We outline an integrated genetic natural resource management (IGNRM) strategy based on hands-on experiences in India for harnessing the untapped potential of rain-fed paddy fallow areas to increase food production, and improve the livelihoods of people with finite and scarce resources by enhancing resource-use efficiency.

TABLE 4.1 Paddy area and paddy fallow area (million ha) by cropping system and water source for Asian regions, 2000-09

Cropping system	South Asia	Southeast Asia	East Asia	Total
Irrigated	30.6	19.6	30.7	80.8
Paddy–Fallow	9.5	0.8	10.2	20.6
Paddy–Other	13.9	1.7	5.7	21.3
Paddy–Paddy or Paddy–Paddy–Paddy	5.7	10.5	5.6	21.8
Paddy–Paddy–Other	1.4	6.5	9.2	17.2
Rainfed	30.7	27.3	2.3	60.3
Paddy–Fallow	21.1	11	2.3	34.4
Paddy–Other	4.2	5.7	0.0	9.9
Paddy–Paddy	5.4	10.6	–	16.0
Grand total	**61.3**	**46.9**	**33.0**	**141.2**

Source: Compiled by IRRI from IRRI (2010); Huke and Huke, 1997; Maclean *et al*., 2002; Gumma *et al*., 2016

4.2 Sustainable intensification of paddy fallows

Paddy remains the most important crop grown in Southeast Asia. Approximately 46.9 million ha or 45 percent of Southeast Asia's cropland is planted to paddy in irrigated (18 million ha), rain-fed (18 million ha), and other cropping systems (see Table 4.1). South Asia accounts for 40 percent of the world's harvested paddy area (USDA, 2010), which supplies almost 25 percent of the world's population (FAO, 2015). The most extensive areas under irrigated paddy are in Indonesia, followed by Viet Nam, the Philippines and Thailand. The largest area under upland paddy is in Indonesia, and significant amounts of land are planted in flood-prone areas in Cambodia, Myanmar and Viet Nam. At present, Southeast Asia produces 150 megatonnes of paddy per year (25 percent of world production), of which 95 percent is consumed within the region. While the per capita demand is expected to decrease in the future, total demand for paddy in Southeast Asia is expected to increase to more than 160 megatonnes per year by 2020 due to population growth (Mutert and Fairhurst, 2002).

In Southeast Asia, paddy is mostly grown in the *kharif* season. A substantial part of this area (15 million ha) remains fallow during the *rabi* (post-rainy) season, primarily due to limited soil moisture availability in the topsoil layer for crop establishment (Subbarao *et al*., 2001). Paddy fallow is the land used to grow paddy in the *kharif* season but left uncropped during the following rabi season. Of the total paddy fallow area in South and Southeast Asia, 2.11 million ha (33 percent of the kharif paddy growing area) is in Bangladesh, 0.39 million ha (26 percent) is in Nepal, and 11.65 million ha (29 percent) is in India. Since paddy is grown on some of the most productive lands in this region, there is scope for increasing the cropping intensity by introducing a second crop during the rabi season using appropriate technologies.

The exact area under paddy fallow per country in Southeast Asia is not available but is needed to plan sustainable intensification. In South Asia, there are approximately 15 million ha of paddy fallow, which is nearly 30 percent of the paddy growing area. In India, nearly 82 percent of the paddy fallow is located in the states of Assam, Bihar, Chhattisgarh, Madhya Pradesh, Orissa and West Bengal. GIS analysis of this fallow land identified diverse soil types and climatic conditions (Kumar Rao *et al*., 2008). The available soil water-holding capacity (1 m soil profile) for most of this land ranges from150-200 mm (Singh *et al*., 2010). If we assume that these soils are fully saturated during most of the paddy-growing season, then there will be residual moisture in the soil at paddy harvest that could be used by the following crop. Wani *et al*. (2009a) reported that these paddy fallows offer a potential niche for legume production due to the considerable amount of available green water after the monsoon, which could be used by a short-duration legume crop after simple seed priming and micronutrient amendments (Kumar Rao *et al*., 2008; Singh *et al*., 2010).

Large areas of land lying fallow for a significant proportion of the calendar year are of particular concern in Southeast Asia for two reasons:

1 The large and growing population of the region requires ever-increasing quantities of locally available food grains and this fallow land represents an under-utilization of agricultural land resources.

2 Continuous cereal cropping, in this case paddy, is unsustainable over time and some form of crop rotation or diversification is desirable for sustainable agricultural production (Paroda *et al*., 1994; Hobbs and Morris, 1996).

Taking advantage of the sufficiently available soil moisture after paddy harvest, growing early-maturing chickpea in paddy fallow areas with best-bet management practices provides an opportunity for intensification (Kumar Rao *et al*., 2008; Harris *et al*., 1999; Wani *et al*., 2011a).

4.3 Challenges for crop intensification in paddy fallow

In most Southeast Asian countries, lowland paddy is grown as a single crop in the wet season, leaving the land fallow during the *rabi* season. However, there is tremendous global pressure to produce at least 50 percent more food to feed the projected world population of 9.15 billion by 2050 (Alexandratos and Bruinsma, 2012). To achieve food and nutritional security, we need to ensure a sustainable, profitable, and resilient smallholder agricultural sector for the growing populations of Asia and Africa (FAO, 2015). However, increasing production by expanding sown areas or through technological means such as supplemental irrigation, fertilizer or mechanization is limited due to increasing pressure on cropland for alternative uses as well as environmental concerns, production costs, and severe stresses on water availability in a changing climate scenario (Garnett *et al*., 2013; Gray *et al*., 2014). In addition, urbanization, industrialization and salinization are putting more pressure on existing crop areas (Foley *et al*., 2011).

In Southeast Asia, after the *kharif* season (June–October) of rain-fed and/or irrigated paddy, the fallow that remains during the *rabi* season (November–February) does not have sufficient residual moisture to grow long-duration staple crops (e.g., paddy, wheat). However, there is an opportunity to grow water-efficient short-season grain legumes, which have a high market demand and can improve soil health via nitrogen fixation (Dabin *et al*., 2016; Dixon *et al*., 2007; Ghosh *et al*., 2007). The success of dry season (post-rainy season) crops generally relies on climatic conditions prevailing during crop establishment and various management practices. The performance of dry season crops is also influenced by limited inputs and management, as well as limited research and extension advice.

Paddy fallow is an underutilized resource of poor farmers with subsistence agricultural practices. There are biophysical, production and socio-economic constraints to promoting the second crop in paddy fallow. Biophysical constraints comprise the persistence of rain-fed ecology, high runoff and low moisture storage, water stagnation/excessive moisture in coastal regions and low residual moisture in dry regions, poor physical condition of topsoil layer due to puddling in paddy fields, development of deep cracks in soil, low soil organic content, and poor microbial activity. Production constraints include the narrow window of opportunity for planting, lack of short-duration and high-yielding varieties, poor plant stands due to poor soil-seed contact in relay sowing, lack of fertilizers/chemicals, severe weed infestations including parasitic weeds, high incidence of diseases, moisture stress, and terminal drought. Socio-economic constraints include traditional practices, such as leaving animals for open grazing after the harvest of *kharif* paddy, the low volume of crop produce, lack of suitable markets for *rabi* crop produce, resource-poor farmers, lack of credit and market infrastructure, non-availability of critical inputs, scarcity of human labour after paddy harvest due to migration to urban areas, and lack of mechanization/draft power.

4.4 Climate-smart food crops or Future Smart Food

As global warming sets in, agricultural production worldwide is projected to fall by 2 percent per decade, as food demand increases by 14 percent. Global bodies are pushing for climate-smart farming with smart crops in a bid to reduce the carbon footprint of agriculture. Dryland cereals and grain legumes branded as smart food crops (ICRISAT, 2017) benefit consumers, farmers and the planet as they diversify farming systems and help smallholder farmers adapt to climate change. We know that climate change is affecting crop production, which will impact farmer livelihoods and food availability. So climate-smart crops and management offer sustainable options to farmers to both adapt to and mitigate climate change (FAO, 2017).

FSF include a variety of warm-season legumes (e.g. soybean, mung bean, black gram, pigeon pea, groundnut) and cool-season legumes (e.g. chickpea, lentil, *khesari* (lathyrus), faba bean, pea) along with nutrient-rich cereals and millets (pearl millet, sorghum, finger millet) that are good candidates for the Southeast Asian region. These low-water-requiring crops need minimal tillage and enhance the organic matter stored in the soil while supporting biological processes, and nutrient and hydrological cycling (Milder *et al*., 2011; Hobbs and Govaerts, 2009), which is critical for increasing agricultural resilience to climate change. The inclusion of FSF crops, such as legumes, into paddy-based cropping systems should improve soil structure and nutrition, providing the basis for paddy yield enhancement. As these crops require less water than paddy, they are good options for additional income. Resilience to climate change depends on the identification of FSF crops and management practices, as well community awareness of their benefits. These crops can contribute to many of the Sustainable Development Goals, which aim to reduce poverty and hunger, improve health and gender equity, promote responsible consumption, and help adapt to climate change.

FSF crops can withstand temperatures in desert-like regions where there are significant differences in day and night temperatures. Specific examples of the advantages of FSF crops include pigeon pea crops, which, when destroyed by unseasonal rain, have the potential for a second flush to produce a good harvest; and pulses, which help to improve soil health through nitrogen fixation and increasing soil microbe diversity, and their leaf droppings provide green manure, help to conserve topsoil and rejuvenate degraded land in severely eroded soils.

In terms of nutritional benefits, FSF include nutri-cereals such as pearl millet, finger millet and sorghum that are high in iron, and pulses play an important role as a main source of dietary protein. The high dietary fibre in pulses lowers the risk of diabetes, heart ailments and gastrointestinal diseases. Pulses also provide substantial amounts of micronutrients (vitamins and minerals) including vitamin E, vitamin B6, folic acid, iron, potassium, magnesium, calcium, phosphorus, sulphur and zinc. Chickpea and pigeon pea are excellent sources of iron, manganese and zinc, and can play a key role in countering iron-deficiency anaemia – a serious health issue, with pregnant women being the most susceptible. More effort is needed to improve the productivity and popularization of FSF, to support farmer seed-sharing networks to ensure availability of diverse crop varieties, and to encourage a diverse farming economy at the landscape level.

4.5 Interventions to harness the potential of paddy fallow

To ensure successful cropping system intensification in paddy fallow, concentrated efforts are needed in the systemic management of the entire paddy-based cropping system and promotion of technological interventions for utilization of paddy fallows.

4.5.1 Managing the planting window

Improving system productivity in paddy-based cropping systems is affected by climate conditions such as rainfall and minimum daily temperatures. Since rain-fed lowland paddy depends on the reliability and amount of rainfall, the growth of subsequent crops can be restricted by low and erratic rainfall. As a result, subsequent crops rely on residual moisture from the wet-season crops. In regions with high rainfall, farmers tend to postpone planting or provide surface drainage to avoid waterlogging. Since planting time is vital for the success of *rabi* crops, targeting the narrow planting window is important, and defined by the interaction between crop growth and environmental conditions. Many studies have shown that good management practices, including planting time adjustment, water management and tillage, could be used to maximize *rabi* season production. However, these practices are time-consuming and expensive. Therefore, we proposed that paddy fallow systems in Southeast Asia are intensified with FSF crops (grain legumes/dry season crops).

The key factors for success in crop intensification is sowing time and the selection of appropriate FSF crops and varieties. In an integrated system, the continued use of long-duration rain-fed paddy (as promoted by paddy breeders who often consider paddy only in isolation) limits the potential for successful sowing of rain-fed *rabi* crops and, therefore, total system productivity. The practice of direct seeding of paddy helps to overcome this limitation as it reduces the time to maturity and opens the window for the successful introduction of FSF crops during the *rabi* season. Paddy varieties with shorter duration (8-10 days) will also help in the successful utilization of residual soil moisture by *rabi* crops.

4.5.2 Balanced plant nutrition

Soil-fertility management needs to be considered along with water-stress management given the fragile nature of the soil resource base (Wani *et al*., 2009a; Sahrawat, Wani and Parthasaradhi, 2010; Sahrawat, Wani and Pathak, 2010), particularly in paddy fallows. Moreover, it is commonly believed that relatively low crop yields in rain-fed soils are obtained because these soils have major nutrient deficiencies, especially lacking nitrogen and phosphorus (El-Swaify *et al.*, 1985; Rego *et al.*, 2003; Sharma *et al.*, 2009). Less attention has been given to diagnosing the extent of secondary nutrient deficiencies such as sulphur and micronutrients in various crop production systems (Rego, Wani and Sahrawat., 2005; Sahrawat, Wani and Rego, 2007, Sahrawat, Wani and Pathak, 2010, Sahrawat *et al.*, 2011) on millions of small and marginal farmers' fields. Since 1999, ICRISAT and its partners have conducted systematic and detailed studies on the diagnosis and management of nutrient deficiencies in the semi-arid regions of Asia with an emphasis on India under the integrated watershed management programme (Wani *et al.*, 2009a). These studies revealed widespread deficiencies in multiple nutrients including micronutrients, such as boron, zinc and sulphur, in 80-100 percent of farmers' fields (Rego, Wani and Sahrawat, 2005; Sahrawat, Wani and Rego, 2007; Sahrawat, Wani and Parthasaradhi, 2010; Sahrawat *et al.*,2011). Research conducted by ICRISAT on sweet sorghum revealed that balanced nutrient management, including the optimum nitrogen dose, enhances yield and significantly improves resource-use efficiency (Sawargaonkar *et al.*, 2013; Sawargaonkar and Wani, 2016). Similarly, on-farm trials conducted in several states of India (Andhra Pradesh, Chattisgarh, Gujarat, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu and Uttar Pradesh) showed that yields significantly increased (30-120 percent) in various crops with soil amendments using micro- and secondary nutrients, which resulted in an overall increase in water and nutrient-use efficiencies (Wani, Ramakrishna and Sreedevi, 2006; Wani *et al.*, 2009a and 2011a; Rego, Sahrawat and Wani. 2007). Similarly, studies on the cultivation of FSF crops in paddy fallow revealed that these crops respond immensely with balanced nutrient management inclusive of secondary and micronutrients. The original concept for site-specific nutrient management was developed in 1996 (Dobermann and White, 1999), and has been tested on irrigated paddy systems in China, India, Indonesia, the Philippines, Thailand, and Viet Nam since 1997. Similar results have been reported from watersheds in China, India, Thailand and Viet Nam (Wani, Pathak and Jangawad, 2003; Wani, Joshi and Raju, 2008; Wani *et al.*, 2009a). In the Thanh Ha watershed in Viet Nam, improved management practices, including balanced nutrient management, increased mung bean yield by 34 percent in 1999–2000, and in the Tad Fa watershed in northeastern Thailand, maize yield increased by 12.3 percent (4.1 tonnes per hectacre) compared to the farmers' normal yield (3.65 tonnes per hectare).

4.5.3 Managing timely seed availability

The overriding challenge for intensification in all six countries is the availability of sufficient seed, particularly for short-duration chickpea. Chickpea is a crop that attracts little private-sector involvement because of its low seed-multiplication rate, production limited to the *rabi* season, and vulnerability to storage pests throughout the intervening rainy season. In addition, the seeds are bulky and difficult to distribute cheaply. Nevertheless, the current high market price for grain makes it attractive for smallholders if they have access to farm-saved or locally produced seeds. National policies that promote crop diversification are in place in some countries (e.g. Bangladesh), but the support for alternative crops is small in comparison to that for staple crops such as paddy. Therefore, the establishment of decentralized but assured quality seed banks, particularly those managed by women self-help groups at village/block level to help alleviate poverty, needs to be promoted.

4.5.4 Ensuring better crop establishment

To harness the optimum yield of FSF, crop establishment needs to improve, and the residual soil water after paddy must be utilized efficiently. The success of crop establishment can be achieved by rapid germination, which relies on soil water content and seed-soil contact. Growing crops with drought and heat tolerance is one method for adapting to the vagaries of climate. The strategy would be to develop a sustainable farmers' participatory seed production system for FSF, and promote improved agronomic management practices, such as seed priming, soil-test-based balanced fertilizer that includes micro and secondary nutrients, biofertilizer, and integrated crop management for better crop establishment in paddy fallow.

Suitable paddy cultivars need to be piloted and identified to help make use of residual moisture for the promotion of short-duration pulses during the *rabi* season. Experimental research and farmers' participatory demonstrations made in the northern states of India (Chhattisgarh, Jharkhand and Orissa) by ICRISAT have shown that short-duration pulses, such as chickpea and blackgram, are suitable for cultivation in paddy fallow and can achieve average yields from 700-850 kg per hectare, provided that suitable varieties and technologies including mechanization for crop establishment are made available. Based on ICRISAT's experience, it is recommended that seed priming, which includes soaking seeds for 4 to 6 hours with the addition of sodium molybdate to the priming water (with further refinement possible), and then sowing with minimum tillage at the optimum seed rate, is used as a simple and effective practice in relay cropping (Musa *et al*., 2001; Harris *et al*., 2002,). Seed priming can enhance seed germination and, therefore, crop growth, plant stand and yield.

4.5.5 Minimum tillage or conservation agriculture

Paddy cultivated as lowland crop on vertisols and associated soils is difficult to till as the soil becomes hard, and farmers are facing difficulties with cultivation during the rainy season. During an ICRISAT initiative in central India on *kharif* fallow, it was found that there is a practice of fallowing vertisols and associated soils in Madhya Pradesh, as well as central India, which accounts for around 2.02 million ha during the *kharif* season (Wani Pathak and Tam, 2002; Dwivedi *et al*., 2003). Therefore, ICRISAT targeted these *kharif* fallows using different management options for minimum tillage, or conservation agriculture, along with a change in cultivar selection.

There is a direct relationship between consumptive water use or evapotranspiration (ET) and crop yield. ET comprises two major processes: non-productive evaporation and productive transpiration (refs). Evaporation cannot be avoided completely but it can be minimized through various field-scale management practices. The three basic elements of conservation agriculture are

1 no or minimum tillage without significant soil inversion;
2 retention of crop residues on the soil surface; and
3 growing crops in rotations appropriate to the soil–climate environment and socio-economic conditions of the region.

On-farm trials on conservation tillage were conducted with short-duration soybean in Madhya Pradesh (Guna, Vidisha, and Indore districts) to intensify the *kharif* fallow areas using suitable landform management (broad bed furrow system). The trials then adopted zero-till planters to sow the succeeding *rabi* chickpea with minimum tillage to enhance the cropping intensity. The results revealed increased crop yields (40-200 percent) and incomes (up to 100 percent) using landform treatments, new varieties and other best-bet management options (Wani, Joshi and Raju, 2008) through crop intensification. Thus for better utilization of residual soil moisture, practices such as zero/minimum tillage and relay planting are recommended. Specially designed machinery, such as the zero-tilled multi-crop planter, can be used effectively to sow in paddy fallow without severely affecting soil moisture.

4.5.6 Improving per unit productivity

Current water-use efficiency (WUE) in agriculture (rain fed and irrigated) can be doubled from 35-50 percent to 65-90 percent with large-scale interventions of scientifically proven management (land, water, crop and pest) options. The *Pradhan Mantri Krishi Sinchayi Yojana* (PMKSY) scheme of the Government of India enables the handling of green and blue water resources together by adopting holistic and integrated water management approaches (Wani, *et al*., 2012, Wani *et al*., 2016.). It is important that all components of the PMKSY scheme be implemented together in rain-fed or irrigated areas with micro watersheds as an implementing unit in the districts. Measures to enhance WUE are discussed elsewhere in this chapter and are reiterated here for continuity:

- efficient use of rainwater stored in soil as soil moisture (green water)
- conjunctive use of blue water through rainwater harvesting in farm ponds
- improved landform for efficient irrigation and water management
- protected cultivation of high-value crops
- soil-test-based integrated nutrient management
- improved crop management practices
- efficient irrigation using micro-irrigation (zero-flood irrigation)
- water-balance-based irrigation scheduling in place of calendar-based irrigation scheduling
- crop rotations and intercrops
- improved crop cultivars (drought tolerant and water efficient)
- integrated pest and disease management
- enabling policies and innovative institutional mechanisms
- organic matter amendments through *in situ* generation of green manuring and composting (vermicomposting and aerobic composting)
- minimum tillage.

Improved method of irrigation system

Despite water scarcity in most farmers' fields in semi-arid tropic locations, water is carried through open channels, which are usually unlined and, therefore, a significant amount of water is lost through seepage. In India, farmers irrigate land rather than crops. For example, for alfisols and other sandy soils with more than 75 percent sand, practices may include the lining of open field channels with some hard cementing material, covering of channels with solar panels as in Gujarat or using irrigation pipes to reduce high seepage and evaporation water losses, and enhance productivity and profitability. The use of closed conduits (plastic, rubber, metallic, and cement pipes) should be promoted (Pathak, Sahrawat and Wani, 2009) to achieve high WUE. Micro-irrigation, in general, is practiced for high-value and horticulture crops. Similarly, micro-irrigation in field crops, including paddy-based cropping systems, should be promoted on a large scale to address the issue of groundwater depletion and water scarcity. Some field trials undertaken in Raichur under the Bhoosamruddhi programme on drip irrigation in paddy revealed that growth parameters (plant height, tiller number, soil plant analysis development and leaf area) improved significantly under sub-surface and surface drip irrigation with laterals spaced 60 cm apart. The highest grain yields of paddy of 10.1 and 9.0 tonnes per hectare were recorded in direct-seeded paddies compared with transplanted paddy under surface drip irrigation with laterals placed 80 cm apart and 60 cm, respectively (Bhoosamruddhi Annual Report, 2016).

Similarly, drip irrigation trials in wheat at Tonk and Udaipur, Rajasthan; and Motavadala, Gujarat showed that 40-50 percent of water could be saved using improved irrigation techniques For water-loving crops, including sugarcane and banana, we need to popularize water-saving technologies, such as drip irrigation, by making them mandatory. In Jharkhand, to use the available water efficiently, drip irrigation was promoted by ICRISAT for vegetable cultivation in Teleya village in Gumla district, which increased the net profit to farmers from Rs 8 000 to Rs 10 000 per acre.

Water balance model-based irrigation scheduling

Needs-based irrigation scheduling can further enhance WUE and crop yields. Farmers, in general, adopt calendar-based irrigation scheduling irrespective of the variability in soil physical parameters (water-holding capacity, soil depth, etc.), resulting in either excess or deficit water application. ICRISAT developed a simple decision-making tool called the 'water impact calculator' (WIC) for irrigation scheduling that requires simple data on the field and its management. The tool provides an irrigation schedule for the entire season as a per water-balance approach (Garg *et al*., 2016).

An ICRISAT-led consortium with local partners (NGOs) and an irrigation company (Jain Irrigation Ltd.) evaluated WIC in farmer participatory field trials between 2010 and 2014 at different sites: Mota Vadala in Jamnagar, Gujarat; Kothapally in Ranga Reddy, Telangana; Parasai-Sindh watershed, Jhansi; Dharola Tonk, Rajasthan, and the ICRISAT research station. Irrigation was scheduled according to WIC calculations, and the exact quantity of water was applied as per recommendations. Deep percolation losses in WIC-managed fields declined by 50-80 percent compared to calendar-based irrigation. Despite applying 30-40 percent less water, WIC-managed fields had comparable yields to controls. For example, at Mota Vadala, Gujarat, Jamnagar in 2011-12, the WIC-managed plot yielded 5.8 tonnes per hectare of wheat compared to 5.9 tonnes per hectare in the calendar-based irrigation plot; in addition, the drip irrigation plot (guided by WIC) yielded 6.3 tonnes per hectare (see Table 4.2). Similar results were recorded in different years at various testing sites; thus, such decision-making tools need to be promoted for optimizing water resources.

Normalization of micro-irrigation policy incentive guidelines

Despite the vast promotion of micro-irrigation by the Government of India, there has been a considerable time lag between the uptake of the subsidy and actual implementation. At present, different government departments or agencies are involved in the implementation of subsidy-oriented schemes. Due to variation in the norms with different states in India, it is difficult to get all the details required by the scheme (Palanisami *et al*., 2011). Moreover, a differential subsidy pattern for different crops, as well as paddy, is being followed in different regions, which is affecting farmers and implementing agencies' ability to follow and avail the benefits of a given scheme. Hence, it is important to introduce a uniform subsidy across the states in India (Palanisami *et al*., 2011).

4.5.7 Social engineering

Awareness raising among farmers that crops can be grown on residual soil moisture after paddy was a major factor in promoting crop intensification in paddy fallows (Joshi *et al*., 2002; Bourai Joshi and Nityanand, 2002). Along with technology demonstrations, and bringing awareness to all stakeholders and policymakers, social engineering is needed to intensify crop production in these fallows by adopting collective action at the cluster level. For effective implementation and scaling-up of sustainable intensification of paddy fallow systems, the development of effective monitoring and evaluation systems is required. These crop intensification technologies should be demonstrated on a pilot basis, followed by a phased-in scale-up to farmer fields. The anticipated impacts of this initiative would be increased farm incomes and improved rural livelihoods, including enhanced nutritional status. Such initiatives would strengthen environmental benefits/ecosystem services,

TABLE 4.2 Experimental results on enhancing water use efficiency

Particulars	Water applied by farmers in WIC-trial fields	Water applied by farmers in WIC-trial fields	Water applied by farmers in traditionally managed control field (calendar-based)
Method of irrigation	Drip	Flood	Flood
1 Mota Vadala, Gujarat			
a Crop	**Wheat**	**Wheat**	**Wheat**
Irrigation water (mm)	460	520	950
Number of irrigations	7	6	13
Crop yield (t ha^{-1})	6.3	5.8	5.9
Deep percolation (mm)	80	150	540
b Crop	**Chickpea**	**Chickpea**	**Chickpea**
Irrigation water (mm)	300	420	580
Number of irrigations	5	6	9
Crop yield (t ha^{-1})	2.2	1.8	1.8
Deep percolation (mm)	50	150	310
2 Dharola, Tonk, Rajasthan			
a Crop	**Wheat**	**Wheat**	**Wheat**
Irrigation water (mm)	260	300	410
Number of irrigations	5	4	5
Crop yield (t ha^{-1})	3.5	3.4	3.5
Deep percolation (mm)	10	30	90
3 Kothapally, Telangana			
a Crop	**Tomato**	**Tomato**	**Tomato**
Irrigation water (mm)	400	590	700
Number of irrigations	9	8	10
Crop yield (t ha^{-1})	8.7	8.3	8.3
Deep percolation (mm)	20	150	220

Source: Wani *et al.*, 2016

including improved land- and water-use efficiencies, and more resilient paddy-based cropping systems with balanced fertilizer inputs and improved soil fertility. At the national level, the Government of India's expenditure of hard currency for pulse importation will decline due to the increased domestic availability of chickpea and other pulses.

To address the prevailing common practice of open animal grazing after the paddy crop harvest in northern and eastern India, concerted efforts were undertaken by ICRISAT in Jharkhand to impart training and awareness building to different stakeholders (including farmers and development agencies), strengthen formal and informal seed systems, and increase access to other inputs to enhance adoption of improved cultivars and technologies. These efforts increased cropping intensity by 25 percent and system productivity by 30-40 percent.

TABLE 4.3 Evaluation of chickpea cultivars in paddy fallows in Jharkhand, post-rainy 2010-13

District	Block	Crop	Variety	Yield (kg ha^{-1})
Gumla	Raideh	Chickpea	KAK 2	1 520
			JG 11	1 340
Seraikella-Kharsawan	Sariekela	Chickpea	KAK 2	1 490
			JG 11	1 280

4.6 Case study: Paddy fallow management in northeastern states of India

The Sir Ratan Tata Trust (SRTT) supported ICRISAT's proposal to increase the impact of development projects in northeastern states of India (Jharkhand, Odisha and Chhattisgarh) by technical backstopping and empowering stakeholders to improve livelihoods through increased agricultural productivity and opportunities via the sustainable use of natural resources. To bridge the gap between the 'desired' and 'achieved' yield, bring quantitative as well as qualitative improvements to fulfil national food needs, sustain the agricultural resource base, and provide livelihood security to millions of rural masses, ICRISAT adopted a holistic system management approach that respects the integrity of ecosystems while humans meet their food needs.

In these targeted pilots, *kharif* paddy was the predominant mono-cropping system, leaving the land fallow during the *rabi* season. Utilization of the paddy fallow is an opportunity that presents considerable scope for crop intensification and to increase farmer incomes. An estimated 11 million ha of paddy area remains fallow during the post-rainy season in the northeastern states of India, providing ample opportunity to enhance land- and water-use efficiency by promoting short-duration pulse/oilseed crops in identified areas. ICRISAT adopted a system approach that linked the farm, as a unit targeting the adoption of modern management practices pertaining to seeds, water, labour, capital or credit, and fertilizer and pesticide use, with other agriculture allied activities for efficient resource management and to enhance system profitability. The pilot addressed the constraints of establishing a succeeding crop and promoted improved paddy cultivars of suitable duration to leave sufficient time for a *rabi* crop.

ICRISAT analysed paddy fallows to identify bottlenecks associated with their effective and sustainable utilization. The analysis showed that sufficient stored moisture remains in the soil after the rainy season crop to grow a post-rainy season crop and that introducing appropriate legumes into paddy fallows is likely to have a significant impact on farmer income. The strategy was promoted to develop a sustainable farmers' participatory seed production system for pulses and to promote improved agronomic (e.g. seed priming, soil-test-based balanced fertilizers including micro and secondary nutrients, biofertilizers, integrated management, etc.) and water conservation practices (e.g. zero/minimum tillage/relay planting) for better crop establishment in paddy fallows.

The scaled-up on-farm research showed that short-duration pulses are suitable for cultivation in paddy fallow and yield as well, provided that suitable varieties and technologies (including mechanization for crop establishment) are available. Participatory trials in Jharkhand state, with the purpose of demonstrating and evaluating chickpea cultivars (KAK 2and JG 11) in post-rainy fallow, yielded 1 490-1 520 kg per hectare for KAK 2 and 1 280-1 340 kg per hectare for JG 11 (see Table 4.3). This indicates that chickpea is a suitable crop to grow after paddy with the benefits of additional income and enhanced rainwater-use efficiency.
An economic analysis showed that growing legumes in paddy fallows is profitable for farmers, with a benefit-cost ratio of greater than 3.0 for many legumes. Such systems could generate 584 million person-days of employment for South Asia and make the region self-sufficient in pulse production.

In several villages in the states of Jharkhand and Madhya Pradesh in India, on-farm participatory research trials sponsored by the Ministry of Water Resources demonstrated enhanced rainfall-use efficiency with paddy fallow cultivation, with total production of 5 600 to 8 500 kg per hectare for two crops (paddy and chickpea). This increased average net income per hectare from INR 51 000 to 84 000 (USD 1 130 to 1 870) (Singh *et al.*, 2010). Similarly it was observed that cultivation of legumes improves soil fertility and has follow-on beneficial effects on paddy performance.
The soil-building integrated approach promoted in the pilot sites emphasized recycling of local materials and reduced reliance on external inputs.

TABLE 4.4 Percent increase in paddy and chickpea yields with improved management from 2007-08 to 2008-09

District	Number of farmers involved	Area sown (ha)	Biomass yield (kg ha^{-1})		Grain yield (kg ha^{-1})		% Increase in grain yield
			Trade	Import	Trade	Import	
Paddy (*Kharif* season)							
Ambikapur	48	15	11 110	12 460	5 520	5 970	8.1
Kanker	36	15	12 930	14 880	6 090	7 370	20.9
Bastar	18	15	8 260	10 100	3 910	5 060	29.4
Chickpea (*Rabi* season)							
Ambikapur	28	4.8	–	480	–	220	–
Kanker	80	19.7	–	1 980	–	1 140	–
Bastar	41	14.3	–	1 020	–	540	–

TABLE 4.5 WUE of Paddy and paddy + chickpea during 2007-08 to 2008-09

District	Rainfall (mm)	Irrigation (mm)	Soil moisture extraction (mm)	WUE (kg ha^{-1} mm^{-1})	
				Trade	Import
Paddy (*Kharif* season)					
Ambikapur	495	9	–	10.9	11.8
Kanker	334	15.5	–	17.4	21.1
Bastar	351	0	–	11.1	14.4
Chickpea					
Ambikapur	512	48	54	–	10.1
Kanker	337	56	25	–	20.3
Bastar	359	45	34	–	12.8

In Chhattisgarh, the on-farm participatory research trials sponsored by the Ministry of Water Resources revealed that the introduction of best management practices such as zero-tilled sowing of *rabi* crops, seed priming, etc. in paddy-based cropping systems enhanced productivity of *rabi* crop and, thereby, total system productivity. Early sowing of paddy along with good management practices increased paddy productivity by 8–29 percent (see Table 4.4) with scope for cultivation of *rabi* crops on the residual moisture.

Significant variation in WUE was recorded for paddy-based cropping system productivity with double cropping. The WUE was calculated as rupees earned per hectare per mm-1 of rainfall. The WUE for paddy ranged from 11.8-21.1 percent (see Table 4.5) and for chickpea ranged from 10.1-20.3 percent, a clear increase in system productivity by adopting cropping system intensification in Chhattisgarh.

In an initiative supported by the Department of Agriculture, Co-operation and Farmers Welfare (DoAC&FW) in India, ICRISAT focused on crop intensification in paddy fallows through the introduction of chickpea, bringing in 3 miillion ha of paddy fallow from the eastern state under FSF crops. DoAC&FW along with ICRISAT conducted a national-level workshop at Bhubaneshwar for scientists, researchers, farmers and policymakers on the introduction of FSF crops to existing single cropping of paddy. In 2016/17, a DoAC&FW-led consortium introduced chickpea to almost 1.8 million ha along with best management practices, including seed priming and mechanized sowing with zero-till multi-crop planters with minimal tillage. The farmers harvested 650-800 kg per hectare of chickpea with net economic benefits ranging from INR. 15 000-20 000 per hectare.

4.7 Conclusion

Paddy fallow offers a potential niche for legume cultivation in Southeast Asia. A combination of short-duration FSF crops holds the key to increased production in paddy-based cropping systems through vertical integration. Cultivation of paddy fallow has the following benefits:

1. Diversification of cropping in paddy fallow is the key to poverty alleviation in this agro-ecosystem and deserves priority attention.
2. Early sowing, minimal tillage and seed priming are effective management options for farmers to grow a rain-fed *rabi* crop in paddy fallow.
3. Regular cultivation of FSF crops improves soil fertility and has follow-on beneficial effects on paddy performance.
4. Additional income, better family nutrition, and increased empowerment as a result of social mobilization will improve farmer wellbeing and capacity to cope with climate change.
5. The presence of ground cover for most of the year reduces the risk of soil erosion.
6. Farmers have more cropping choices and land-use options that will help increase agro-biodiversity and improve system resilience.

Sustainable intensification of paddy fallow is an urgent need and should be effectively addressed to ensure food security.

REFERENCES

Alexandratos, N. & Bruinsma, J. 2012. *World Agriculture Towards 2030/2050: The 2012 Revision*.

Anantha, K. H. & Wani S. P. 2016. Evaluation of cropping activities in the Adarsha watershed project, southern India. *Food Security*, 8 (5), pp. 885-897.

Barron, J. & Keys P. 2011. Watershed management through a resilience lens. Chapter 12 In *Integrated Watershed Management*. S. P. Wani, J. Rockström, and K. L. Sahrawat eds. pp. 391-420. CRC Press. The Netherlands.

Barron, J., Rockström J. & Gichuki F. 2003. Dry spell analysis and maize yields for two semi-arid locations in East Africa. *Agriculture and Forest Meteorology*. 117(1-2): 23-37.

Bhoosamruddhi Annual Report. 2016. *Improving Rural Livelihoods through Innovative Scaling-up of Science-led Participatory Research for Development*. report submitted to Government of Karnataka, 2016.

Bourai, V. A., Joshi, K. D. & Nityanand K. 2002. *Socioeconomic Constraints and Opportunities in rainfed post rainy (rabi) cropping in Paddy fallow areas of Nepal*. submitted to International Crops Research Institute for the Semi-Arid Tropics, Patancheru. (also available at www.researchgate.net/publication/237546039).

CGIAR. *Research Program on Climate Change, Agriculture and Food Security*. (CCAFS). (also available at www. ccafs.cgiar. org/commission).

Dabin, Z., Pengwei, Y., Na, Z., Changwei, Y., Weidong, C. & Yajun K. 2016. Contribution of Green Manure Legumes to Nitrogen Dynamics in Traditional Winter Wheat Cropping System in the Loess Plateau of China. *European Journal of Agronomy* 72: pp. 47-55.

Dixon, J., Omwega, A. M. Friel, S., Burns, C., Donati K. & Carlisle, R. 2007. The Health Equity Dimensions of Urban Food Systems. *Journal of Urban Health* 84: pp. 118-129.

Dobermann, A. & White P.F. 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. *Nutr. Cycl. Agroecosyst*. 53: 1-18.

Dwivedi, R. S., Ramana, K. V., Wani S. P. & Pathak, P. 2003. Use of Satellite Data for Watershed Management and Impact Assessment. In Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia, S. P. Wani, A. R. Maglinao, A. Ramakrishna and T. J. Rego, eds. pp.149-157. P*roceedings of the ADB-ICRISAT-IWMI Project Review and Planning Meeting, Hanoi, Viet Nam, 10-14 Dec 2001*. Patancheru, 502 325, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

El-Swaify, S. A., Pathak, P., Rego, T. J. & Singh, S. 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Advances in Soil Science* 1:1-64.

Falkenmark, M. 1997. Meeting water requirements of an expanding world population. *Philosophical Transactions of the Royal Society of London*. 352:929-936.

Falkenmark, M. & Rockström, J. 2008. Building resilience to drought in desertification-prone savannas in sub-Saharan Africa: The water perspective. *Natural Resources Forum* 32:93-102.

FAO. 2002. Rome, Italy. ftp://ftp.fao.org/docrep/fao/005/y7352e/y7352e00.pdf

FAO. 2012. *Economics of plant genetic resource management for adaptation to climate change*. A review of selected literature, by S. Asfaw and L. Lipper. (also available at http://www.fao.org/docrep/015/an649e/an649e00.pdf).

FAO. 2017. *The future of food and agriculture: Trends and challenges*. FAO Rome. (also available at www.fao.org/3/a-i6583e.pdf).

FAO-PAR. 2011. *Biodiversity for food and agriculture: contributing to food security and sustainability in a changing world*. Platform for Agrobiodiversity. Rome. (also available at http://agrobiodiversityplatform.org/files/2011/04/PAR-FAO-book_lr.pdf).

FAOSTAT. 2010. http://faostat.fao.org/site/567/default.asp.ancor. Accessed date. April 2010.

FAOSTAT. 2012. *FAO statistical yearbook*. (also available at www.fao.org/docrep/015/i2490e/i2490e00.htm).

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett. E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D. & Zaks D.P.M. 2011. Solutions for a cultivated planet. *Nature*. 478, pp.337-342.

Frockling S., Roulet, N. T., Moore, T. R., Richard, P. J. H., Lavoie, M. & Muller, S.D. 2001. Modelling northern peatland decomposition and peat accumulation. *Ecosystems* (NY, Print) 4(5):479-498. doi:10.1007/s10021-001-0105-1.

Garg, K. K., Wani, S. P. & Patil, M.D. 2016. Simple and farmer-friendly decision support system for enhancing water use efficiency in agriculture: tool development, testing and validation. *Current Science*. 110 (9), 1716-1729.

Garnett, T., Appleby, M. C., Balmford, A., Bateman, A. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J. & Godfray H.C.J. 2013. Sustainable Intensification in Agriculture: Premises and Policies. *Science*, 341: 2013.

Ghosh, P., Bandyopadhyay, K., Wanjari, R., Manna, M., Misra, A., Mohanty, M. & Rao A.S. 2007. Legume Effect for Enhancing Productivity and Nutrient Use-efficiency in Major Cropping Systems – An Indian Perspective: A Review. *Journal of Sustainable Agriculture* 30: 59-86.

Gordon, L.J., Steffen, W. & Jonsson, B.F. 2005. Human modification of global water vapor flows from the land surface. Proc. Natl. Acad. Sci. USA 102:7612-7617.

Gray, J., Friedl, M., Frolking, S., Ramankutty, N., Nelson, A. & Gumma, M. 2014. Mapping Asian Cropping Intensity with MODIS. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 7 (8): 3373–3379. doi:10.1109/JSTARS.2014.2344630.

Gumma, M.K., Thenkabail, P.S, Pardharsadhi T., Rao, M.N., Mohammed, I.A., & Whitbread, A.M. 2016. Mapping Paddy – fallow cropland areas for short season grain legumes intensification in South Asia using MODIS 250 m time-series data. *International Journal of Digital Earth*, 9 (10): 981-1003.

Harris, D., Tripathi, R. S. & Joshi, A. 2002. 'On-farm' seed priming to improve crop establishment and yield in dry direct-seeded rice. pp. 231-240 in: S., Pandey, M., Mortimer, L., Wade, T. P., Tuong, K., Lopez, and B. Hardy, eds. 2002. *Proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities, 25-28 January 2000*, Bangkok, Thailand. Los Banos (Philippines): International Rice Research Institute. 383 pp.

Harris, D., Joshi, A., Khan, P. A., Gothkar, P. & Sodhi, P.S. 1999. On-farm seed priming in semi-arid agriculture: development and evaluation in maize, Paddy and chickpea in India using participatory methods. *Experimental Agriculture* 35:15-29.

Hobbs P.R. & Govaerts, B. 2009. *How conservation agriculture can contribute to buffering climate change. Climate Change and Crop Production*. R. M. Wallingford ed. CAB International, Oxford, UK, pp.177-199.

Hobbs, P.R. & Morris, M.L. 1996. *Meeting South Asia's Future Food Requirements from Rice-Wheat Cropping Systems: Priority Issues Facing Researchers in the Post Green Revolution Era*. NRG Paper 96-01. Mexico, D.F.: CIMMYT

Huke, R.E. & Huke, H.E. 1997. *Rice Area by Type of Culture: South, Southeast, and East Asia maps*. International Rice Research Institute, Manila.

ICRISAT. 2017. *Making Smart Food Choices*. (also available at www.icrisat.org/wp-content/uploads/2017/04/Smart-food-flyer_Global_web.pdf).

Intergovernmental Panel on Climate Change. 2007. Technical Summary. In Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. Cambridge, UK, and New York, USA, Cambridge University Press.

Intergovernmental Panel on Climate Change. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, eds. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 582.

International Food Policy Research Institute. 2009. *Climate change: impact on agriculture and costs of adaptation*. (also available at www.ifpri.org/publication/climate-change-impact-agriculture-and-costsadaptation).

Joshi, P. K., Jha, A.K., & Wani, S.P. 2008. Impact of watershed program and conditions for success: A meta-analysis approach. In Global theme on agroecosystems, Report no. 46. *Patancheru* 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Joshi, P.K., Pratap, B. & Vinay A.B. 2002. Socioeconomic constraints and opportunities in rainfed post rainy (*rabi*) cropping in Paddy fallow areas of India. International Crops Research Institute for the Semi-Arid Tropics, *Patancheru*. 502 (324): 58.

Karlberg, L., Rockström, J. & Shiklomanov M. 2009. Water Resource Implications of Upgrading Rainfed Agriculture – Focus on Green and Blue Water Trade-offs. In Rainfed agriculture: Unlocking the potential, S. P. Wani, J. Rockström, and T. Oweis, eds.1-310. *The Comprehensive Assessment of Water Management in Agriculture Series, Volume 7*. Wallingford, UK: CABI.

Kumar, R. & Gautam, H.R. 2014 Climate Change and its Impact on Agricultural Productivity in India. *Journal of Climatology and Weather Forecasting* 2:109. doi:10.4172/2332-2594.1000109.

Kumara, C., Moses S., Bantilan C., Borikar S.T., Kumar A. & V. S. Reddy B. 2016. *Rainy Season Sorghum Technology Adoption and Impact Study in Maharashtra*. Research Report 70. Patancheru 502 324. Telangana, India: International Crops Research Institute for the Semi-Arid Tropics. 80 pp. ISBN 978-92-9066-580-9. (also available at http://oar.icrisat.org/9887/1/Rainy%20Season%20Sorghum%20Technology%20merge%20file.pdf).

Kumar Rao. D.K., Harris, D., Kankal, M. & Gupta, B. 2008. *Extending post rainy (rabi) cropping in Paddy fallows of eastern India. In Improving agricultural productivity in Paddy -based systems of the High Barind Tract of Bangladesh*, C. R. Riches, D. Harris, D. E. Johnson, and B. Hardy eds, 193-200. Los Banos, Philippines: International Paddy Research Institute.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. & Naylor R.L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319 (5863): 607-610.

Maclean, J.L., Dawe, D.C., Hardy, B. and Hettel, G.P. eds. 2002. Rice almanac (Third Edition). Philippines, IRRI, WARDA, CIAT and FAO.

Mahato, A. 2014. Climate Change and its Impact on Agriculture. *International Journal of Scientific and Research Publications*, 4(4): 1-6.

Milder, J.C., Majanen, T., & Scherr, S.J. 2011. Performance and Potential of Conservation Agriculture for Climate Change Adaptation and Mitigation in Sub-Saharan Africa. Ecoagriculture Discussion Paper no. 6. 2011, EcoAgriculture Partners, Washington, DC.

Musa, A.M., Harris, D., Johansen, C. & Kumar, J. 2001. Short duration chickpea to replace fallow after aman Paddy: the role of on-farm seed priming in the High Barind Tract of Bangaladesh. *Experimental Agriculture*, 37(4): 509-521.

Palanisami, K., Giordano, M., Kakumanu, K. & Ranganathan, C. T. 2011. The stabilization value of groundwater: evidence from Indian tank irrigation systems. *Hydrogeology Journal*, DOI 10.1007/s10040-011-0793-3. Nov. 4.

Paroda, R.S. 1994. Sustainability of Rice-wheat Production Systems in Asia. Agriculture Organization of the United Nations Bangkok, *RAPA Publication*, 1994: 1-55.

Pathak, P., Sahrawat, K.L., & Wani, S.P. 2009. Opportunities for water harvesting and supplemental irrigation for improving rain-fed agriculture in semi-arid areas. In Rain-fed agriculture: Unlocking the potential. Comprehensive assessment of water management in agriculture series. S. P. Wani, J. Rockström, and T. Oweis eds, pp. 197-221. Wallingford, UK: CAB International.

Postel, S.L., Daily, G. C., & Ehlich, P. R. 1996. Human appropriation of renewable fresh water. *Science* 271:785-788.

Rao, K. & Wani, S.P. 2010. Climate change and management measures – global perspectives, climate change and adaptation strategies in the SAT. *In Proceedings of the Seminar on 'Future Farming'*, State Horticulture Mission-Kerala, Thiruvananthapuram, 2010, pp. 13-22.

Rao, K. V., Venkateswarlu, B., Sahrawath, K.L., Wani, S.P., Mishra, P.K., Dixit, S., Reddy, K.S, Kumar, M. & Saikia, U.S. 2010. *Proceedings of National Workshop-cum-Brainstorming on Rainwater Harvesting and Reuse through Farm Ponds: Experiences, issues and strategies*. April 21-22, 2009, CRIDA, Hyderabad: CRIDA.

Rego, T.J., Sahrawat, K.L. & Wani, S.P. 2007. Widespread deficiencies of sulfur, boron and zinc in Indian semi-arid tropical soils: On-farm crop responses. *Journal of Plant Nutrition* 30:1569-1583.

Rego, T. J., Wani, S. P. & Sahrawat, K.L. 2005. Macro-benefits from boron, zinc, and sulphur application in Indian SAT: A step for grey to green revolution in agriculture. Global Theme on Agroecosystems Report no. 16. *Patancheru*, Andhra Pradesh, India: ICRISAT.

Rego, T. J., Rao V.N., Seeling, B., Pardhasaradhi, G. & Kumar Rao J.V.D.K. 2003. Nutrient balances – a guide to improving sorghum and groundnut-based dryland cropping systems in semi-arid tropical India. *Field Crops Research* 81:53-68.

Rockström, J. & Gordon, L. 2001. Assessment of Green Water Flows to Sustain Major Biomes of the World: Implications for Future Ecohydrological Landscape Management. *Phys. Chem. Earth* 8 (26)(11-12):843-851.

Rockström, J., Gordon, L. & Folke, C. 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conservation Ecology* 3(2):5.

Rockström, J., Hatibu, H. & Oweis, T. 2007. *Managing water in rain-fed agriculture. In Water for food, water for life: A comprehensive assessment of water management in agriculture*, D. Molden ed. pp. 315-348. London: Earthscan and Colombo. International Water Management Institute (IWMI).

Rockström, J. Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E. F., Leton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A. Hughes, T., Van der Leewu, S., Rodhe, H., Sörlin, S. Snyder, P.K., Costanza, R. Svedin, U., Falkenmark, L., Corell, R. W., Fabry, V.J, Hansen, J. Walker, B., Liverman, D., Richardson, K. Crutzen, P. & Foley, J. A. 2009. A safe operating space for humanity. *Nature* 461, 472-475. 10.1038/461472a Medline doi:10.1038/461472a.

Ruchita S. & Rohit, S. 2017. Effect of Global warming on Indian Agriculture. *Journal of Climatology and Weather Forecasting* 5:195. doi: 10.4172/2332-2594.1000195.

Sahrawat K.L., Wani, S.P. & Pathak, P. 2010a. Managing natural resources of watersheds in the semi-arid tropics for improved soil and water quality: A review. *Agricultural Water Management* 97:375-381.

Sahrawat, K.L., Wani, S. P. & Rego, T.G. 2007. Widespread deficiencies of sulphur, boron and zinc in dryland soils of the Indian semi-arid tropics. *Current Science* 93(10):1-6.

Sahrawat, K.L., Wani, S.P. & Parthasaradhi, G. 2010. Diagnosis of secondary and micronutrient deficiencies and their management in rainfed agroecosystems: Case study from Indian Semi-arid Tropics. *Soil Science and Plant Analysis* 41:1-15.

Sahrawat, K.L., Wani, S.P., Subba Rao, A. & Pardhasaradhi, G. 2011. *Management of emerging multinutrient deficiencies: A prerequisite for sustainable enhancement of rainfed agricultural productivity*. Chapter 9. In Integrated Watershed Management. S. P. Wani, J. Rockström, and K. L. Sahrawat eds, pp. 281-314. The Netherlands: CRC Press.

Sawargaonkar, G.L. & Wani, S.P. 2016. Nitrogen response of sweet sorghum genotypes during rainy season. *Current Science*, 110 (09): pp. 1699-1703.

Sawargaonkar, G.L. Patil, M.D. Wani,S. P., Pavani, E. Reddy, B.V.S.R. & Marimuthu, S. 2013. Nitrogen response and water use efficiency of sweet sorghum cultivars. *Field Crops Research*, 149: 245-251. (also available at https://doi.org/10.1016/j.fcr.2013.05.009)

Sharma, K.L., Grace, J.K. & Srinivas, K. 2009. Influence of tillage and nutrient sources on yield sustainability and soil quality under sorghum-mung bean system in rainfed semi-arid tropics. *Communications in Soil Science and Plant Analysis*. 40:2579-2580.

Shiklomanov, I. 1993. *World fresh water resources. In Water in Crisis: A Guide to the World's Fresh Water Resources*, P. H. Gleick ed. 13-24. New York: Oxford University Press.

Singh, P., Pathak, P., Wani, S.P. & Sahrawat, K.L. 2010. *Integrated watershed management for increasing productivity and water use efficiency in semi-arid tropical India*. in Water and Agricultural Sustainability Strategies Manjit S Kang, Ed. CRC Press, The Netherlands. pp. 181-205

Stewart, J. B. 1977. Evaporation from the wet canopy of a pine forest, *Water Resources research*. 13: 915-921, 1977.

Subbarao, G.V., Kumar Rao J.V.D.K., Kumar, J., Johansen, C., Deb, U.K., Ahmed, I., Krishna Rao, M.V.,

Venkataratnam L., Hebbar, K.R. & Sesha Sai, M.V.R. 2001. Spatial distribution and quantification of Paddy-fallows in South Asia – potential for legumes. 502324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 316 pp. ISBN 92-9066-436-3.

Thornton P. 2012. Recalibrating Food Production in the Developing World: Global Warming Will Change More Than Just the Climate. CCAFS Policy Brief no. 6. CGIAR Research Program on Climate Change. *Agriculture and Food Security* (CCAFS). (also available at https://cgspace.cgiar.org/handle/10568/24696).

United Nations Framework Convention on Climate Change. 2007. Climate change: impacts, vulnerabilities and adaptation in developing countries. (also available at http://unfccc.int/resource/docs/publications/impacts.pdf)

USDA. 2010. United States Department of Agriculture. Foreign Agricultural Service. (also available at www.fas.usda.gov/psdonline/)

Wani, S.P., Anantha, K.H. Garg, K.H., Joshi, K.H., Sohani, K.H., Mishra, P.K., & Palanisami, K. 2016. *Pradhan Mantri Krishi Sinchai Yojana: Enhancing Impact through Demand Driven Innovations*, Research Report IDC-7. Technical Report. ICRISAT, Patancheru.

Wani, S.P., Anantha, K.H. & Sreedevi, K.H. 2011a. Assessing the Environmental Benefits of Watershed Development: Evidence from the Indian Semi-Arid Tropics. *Journal of Sustainable Watershed Science and Management*: 1(1):10–20.

Wani, S.P., Garg, K.K., Singh, A.K. & Rockström, J. 2012. Sustainable management of scarce water resource in Tropical rainfed agriculture. *Advances in soil science*, 347-403.

Wani, S.P., Joshi, P.K. & Raju, K.V. 2008. *Community watershed as a growth engine for development of dryland areas. A comprehensive assessment of watershed programs in India*. Global Theme on Agroecosystems Report No. 47. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Wani, S.P., Pathak, P. & Jangawad, L.S. 2003. Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19:217–222.

Wani, S.P., Pathak, P. & Tam, H.M. 2002. Integrated watershed management for minimizing land degradation and sustaining productivity in Asia. In Integrated land management in dry areas. Zafar Adeel ed. pp. 207-230. Proceedings of a joint UNU-CAS international workshop, September 8-13, 2001, Beijing, China.

Wani, S.P., Ramakrishna, Y.S. & Sreedevi, T.K. 2006. Issues, concepts, approaches and practices in integrated watershed management: Experience and lessons from Asia. In: Integrated management of watersheds for agricultural diversification and sustainable livelihoods in Eastern and Central Africa, 17-36. *Proceedings of the international workshop held at ICRISAT, December 6-7, 2004, Nairobi, Kenya*. Patancheru, Andhra Pradesh, India: ICRISAT.

Wani, S.P. & Rockström, J. 2011. *Watershed development as a growth engine for sustainable development of dryland areas*. In Integrated Watershed Management in Rainfed Agriculture, S. P. Wani, J. Rockström, and K. L. Sahrawat eds. pp. 35-52. The Netherlands: CRC Press.

Wani, S.P., Rockstrom, J. & Sahrawat, K.L. 2011. *Application of new science tool*. In integrated watershed management for enhancing impacts, published in 'Integrated Watershed Management in Rainfed Agriculture', CRC Press.

Wani, S.P., Rockström, J. & Venkateswarlu, B. 2011. *New Paradigm to Unlock the Potential of Rainfed Agriculture in the Semiarid Tropics*. In World Soil Resources and Food Security, R. Lal, and B.A. Steward eds. pp. 419-470. UK: CRC Press.

Wani, S.P., Sreedevi, T.K. & Marimuthu, S. 2009. *Harnessing the potential of Jatropha and Pongamia plantations for improving livelihoods and rehabilitating degraded lands*. 6th international biofuels conference, March 4-5, 2009.

Wani, S.P., Sreedevi, T.K. & Rockström, J., *et al*. 2009. Rain-fed agriculture – Past trends and future prospects. In Rain-fed agriculture: Unlocking the potential. S. P. Wani, J. Rockström, and T. Oweis eds. 1-35. Comprehensive Assessment of Water Management in Agriculture Series. Wallingford, UK: CAB International.

World Bank. 2008. Agriculture and poverty. Agriculture for Development Policy Brief. (also available at worldbank.org/SOUTHASIAEXT/Resources/223546-1171488994713/3455847-1192738003272/Brief_AgPovRedctn_web.pdf)