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Managing Water and Soils to Achieve Adaptation and Reduce Methane Emissions and Arsenic Contamination in Asian Rice Production

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Abstract: Rice production is susceptible to damage from the changes in temperature and rainfall patterns, and in the frequency of major storm events that will accompany climate change. Deltaic areas, in which millions of farmers cultivate from one to three crops of rice per year, are susceptible also to the impacts of a rising sea level, submergence during major storm events, and saline intrusion into groundwater and surface water resources. In this paper, I review the current state of knowledge regarding the potential impacts of climate change on rice production and I describe adaptation measures that involve soil and water management. In many areas, farmers will need to modify crop choices, crop calendars, and soil and water management practices as they adapt to climate change. Adaptation measures at the local, regional, and international levels also will be helpful in moderating the potential impacts of climate change on aggregate rice production and on household food security in many countries. Some of the changes in soil and water management and other production practices that will be implemented in response to climate change also will reduce methane generation and release from rice fields. Some of the measures also will reduce the uptake of arsenic in rice plants, thus addressing an important public health issue in portions of South and Southeast Asia. Where feasible, replacing continuously flooded rice production with some form of aerobic rice production, will contribute to achieving adaptation objectives, while also reducing global warming potential and minimizing the risk of negative health impacts due to consumption of arsenic contaminated rice.

Keywords: aerobic rice; climate change; deltas; Mekong; mitigation; sustainable rice intensification

1. Introduction

Rice is the primary food crop for much of humanity, and rice production supports millions of livelihoods across Asia and in portions of Africa [1–5]. Rice production is moderately susceptible to damage from climate change. Rising temperatures and changes in the amount and timing of rainfall can impair plant growth and reduce crop yields [6–8]. The increasing atmospheric concentration of CO_2 will enhance plant growth in some areas, with positive implications for crop yield, but the net impact of climate change will be negative in areas where the yield impairment due to rising temperatures or changing rainfall patterns is substantial. In regions as large and diverse as Asia and Africa, the impacts of climate change on rice production will vary with location and with differences in regional weather patterns and crop production settings [9].

Much of the rice production in South and Southeast Asia is found in the deltas formed by major rivers, such as the Mekong, Irrawaddy, Chao Phraya, and Ganges-Brahmaputra [10]. Rice is well adapted to these deltaic regions, many of which are characterized by monsoonal climates. Rice plants can tolerate extended periods in which the paddy soils are flooded or partly submerged, yet they are susceptible to damage from complete submergence caused by short-term or extended flooding [11–15].

The 2011 Southeast Asian flood caused water levels in Cambodia's Tonle Sap Lake to rise above normal for more than one month, destroying 12% of the area planted in rice in Battambang Province, with notable implications for livelihoods and food security in the region [16]. The frequency of such flooding is expected to increase with climate change [17–19]). In sum, rice production is susceptible to yield impairment due to several aspects of climate change, including changes in rainfall patterns, higher temperatures, and an increase in the frequency and severity of flooding events.

My goal in this paper is to describe adaptation measures that will assist in minimizing the potential damage to rice production from climate change, with a particular emphasis on soil and water management. I begin by reviewing the current state of knowledge regarding the direct and indirect impacts of climate change on rice production systems. The discussion includes many examples of climate change impacts and adaptation efforts already observed in several countries. I describe also the potential role of soil and water management in reducing the amount of methane generated and released from rice paddies each year and in reducing also the uptake of arsenic by rice in areas with high concentrations of arsenic in soils and groundwater. I conclude that improvements in soil and water management might be helpful in achieving several desirable objectives, including climate change adaptation and mitigation, and reducing a notable risk to public health in portions of South and Southeast Asia.

2. Climate Change and Rice Production

Climate change will impact rice production through a combination of direct and indirect effects. The direct effects include the implications of higher temperatures and changes in ambient carbon dioxide concentrations on the growth, development, and yield of rice plants [20,21]. Additionally in this category are the impacts of changes in rainfall patterns, humidity, solar radiation, and average wind speeds, which influence rice growth and grain yields [22–25]. The indirect effects include changes in crop water requirements and in water availability, particularly in areas where rice is irrigated. The impacts of sea level rise, coastal erosion, and saline intrusion into coastal aquifers also are among the indirect impacts of climate change on rice production [10,17].

2.1. Direct Effects

Climate change will impact rice production through increases in minimum and maximum temperatures, changes in the timing, duration, and intensity of rainfall events in basins where rice is cultivated, and the increasing concentration of CO_2 in the atmosphere [26–28]). While higher ambient concentrations of CO_2 can enhance crop yields, higher temperatures at critical stages of crop development can impair spikelet fertility and thus offset the potential increase in crop yields [29–33]. Higher CO_2 concentrations can exacerbate the sterility impacts of higher temperatures by reducing the number of pollen grains deposited on the stigma [34]. The net effects of changes in temperature and CO_2 concentrations likely will be negative in some locations and seasons, and positive in others, with variation across temperate and tropical climates [6,27].

In a controlled environment chamber experiment conducted at the University of Florida, Baker *et al.* [35] observed only small yield increases in response to CO_2 enrichment, while higher temperatures notably reduced grain yields of the IR-30 rice cultivar. Cheng *et al.* [20], also using controlled environment chambers, showed that high night temperatures limit grain setting of the IR-72 cultivar, thus reducing the yield enhancing advantages of higher CO_2 concentrations. Cai *et al.* [36] found that higher temperatures fully offset the potential gains in rice yields from higher levels of CO_2, in a two-year, free-air CO_2 enrichment (FACE) experiment in Jiangsu Province, China. Rice yields were reduced by 35% in 2013 and by 17% in 2014, at increased levels of both CO_2 and temperature. The number of filled grains per m^2 was significantly smaller in the presence of higher CO_2 and higher temperature. The authors recommend research to increase the proportion of filled grains (or spikelet fertility) and grain number per m^2, to prevent yield reductions due to climate change [36]. Wang *et al.* [37] report an average 4.7% reduction in rice yield, when both CO_2 and temperature were increased, over the course of a four-year field experiment with a *japonica* hybrid cultivar, also in Jiangsu Province.

In areas where rainfall increases with climate change, rice yields might increase, although there might be offsetting impacts due to higher temperatures, particularly at night and during the booting, flowering, and grain-filling stages of production [10,26,38,39]. Higher humidity, in combination with higher temperatures, also can cause spikelet sterility and reduce grain quality [40,41]. Higher night temperatures had a larger, negative impact on rice yields and 1000-grain weights on two *indica* varieties in China, than did higher daytime temperatures [42].

Higher temperatures already impact rice production in tropical areas, resulting in smaller yields and lower grain quality [21]. The higher temperatures and increases in vapor pressure deficit that will accompany climate change can increase chalkiness, thus reducing head rice yields, particularly during the wet season, when humidity is high [43]. Both chalkiness and head rice yields are important quality characteristics that influence the prices farmers obtain for their rice [42,44]). Okada *et al.* [45] attribute the decline in rice quality observed in Western Japan since the 1990s to an increase in the occurrence of chalky grains. Dong *et al.* [46] observed significant yield reductions, smaller head rice yields, and increased chalkiness, due to higher night temperatures in a pot culture experiment in Jiangsu Province, China. Some of the impacts they observed varied across the two *indica* and *japonica* cultivars they tested, and with the position of rice grains on the panicle. Grain filling was significantly depressed on inferior kernels, while the filling rate for superior kernels was largely unchanged. The negative impacts of higher temperatures on grain yield and quality were more severe on the *japonica* variety than on the *indica* variety, suggesting that *indica* varieties might be more adaptable to higher temperatures [46].

Indeed, the impacts of higher night temperatures on rice yields might be smaller on the *indica* cultivars that are common in the tropics, than on the *japonica* varieties, which were developed in cooler regions (Dong *et al.* [46]). Some time ago, Weng and Chen [47] observed higher rates of photosynthesis, in the presence of higher temperatures, in *indica* varieties than in *japonica* varieties in an experimental setting. Peraudeau *et al.* [48] found that although night respiration increases with higher temperatures, the reduction in carbon assimilation and dry matter production is negligible with *indica* cultivars. Shah *et al.* [39] observed reductions in grain yield of 0% and 10% in 2009, and 17% and 45% in 2010, for *indica* and *japonica* varieties, respectively, in a field-scale experiment involving a 2 °C increase in night temperatures. The implications of higher night temperatures on carbon assimilation and grain yields are not yet fully understood. Welch *et al.* [49] propose additional research that investigates the impacts of minimum and maximum temperatures jointly, as the two temperatures can have offsetting impacts on rice yields.

In a simulation study of the potential impacts of climate change on rice production in the Mekong River basin, Mainuddin *et al.* [50,51] show that the yields of rainfed rice might increase in the upper portion of the basin (Laos and Thailand), while declining in the lower portion (Cambodia and Vietnam), due largely to changes in rainfall patterns and in ambient CO_2 concentrations. The yields of irrigated rice in the Mekong River basin might be largely unaffected by climate change, if the projected increases in irrigation requirements can be satisfied [50]. The authors show also that some of the projected negative impacts on rainfed rice can be offset by implementing adaptation options, including changes in rice planting dates, increases in fertilizer applications, and provision of supplemental irrigation.

2.2. Indirect Effects

Several authors have examined the likely indirect effects of climate change on crop water requirements and water availability, largely with the aid of simulation models that project future conditions, in conjunction with prevailing climate change scenarios. Using such models for selected countries, Döll [52] projects that net irrigation requirements will increase notably in some countries and regions, while declining somewhat in others. The highest requirements will occur in hot, arid regions, such as northern Africa, while the lowest irrigation requirements will occur in cooler, humid regions, such as northern Europe and Southeast Asia. The projected changes in irrigation requirements are modified somewhat by changes in cropping patterns and crop calendars. For example, in some regions where the average annual temperature will increase and annual rainfall will decline with climate change, the net irrigation water requirement might also decline if farmers select alternative crops or shift their cultivation schedules to cooler, wetter portions of the year [52].

Elgaali *et al.* [53] also recommend changes in cropping patterns and crop calendars as adaptation responses to the increases in irrigation water requirements they project for the Arkansas River Basin in Southeastern Colorado. In that region, substantial increases in temperature and evapotranspiration will lead to higher irrigation water requirements in the spring season, while increases in humidity and reductions in solar radiation will reduce irrigation requirements in summer [53]. The net effect will be an increase in annual irrigation water requirements. Hence, in addition to adjusting their cropping patterns and crop calendars, farmers and water managers might invest also in new efforts to capture and store rainfall, and manage soil moisture effectively across seasons [53].

Estimates of changes in monthly weather conditions form the basis of the climate change projections prepared by Rehana and Mujumdar [54] for the Bhadra Reservoir command area in the Indian state of Karnataka. Irrigation water demands in rice production, which occurs from April through October, are expected to increase with climate change. The same is true for sugarcane production, although irrigation demands will increase in some months, while declining in others.

Shahid [55] examines monthly water use by rice in Bangladesh, where about 60% of the annual crop is produced during the *Boro* season, which occurs from January through May. This is the dry season in Bangladesh, such that all of the *Boro* rice is irrigated [56]. Climate change will bring higher temperatures and higher rates of evapotranspiration during the *Boro* season, thus increasing daily crop water requirements. However, the higher rates of evapotranspiration will modify the crop physiology and shorten the growing season, thus reducing the number of irrigation days [55]. Effective rainfall is projected to decline during January and February in northwestern Bangladesh, while increasing in March, April, and May. The projected net change in effective rainfall is positive [55]. The summary effect of these projected changes in evapotranspiration, effective rainfall, and irrigation days is largely neutral. The projected average irrigation water requirements for 2025, 2050, 2075, and 2100 are 1059 mm, 1036 mm, 1043 mm, and 1044 mm, respectively [55].

Mainuddin *et al.* [57] also project a small impact of climate change on the net irrigation requirement of *Boro* rice and other crops in Bangladesh. Using a daily water balance model, the authors estimate irrigation water requirements for all districts in the country, for average and dry climate conditions. The projected changes in rainfall, due to climate change, are quite small during the *Boro* season, such that changes in evapotranspiration largely determine the likely impact on net irrigation requirements. The authors project an average increase in the net irrigation requirement for *Boro* rice of 3%, with a maximum increase of 5% in some districts, in their dry conditions scenario. The projected average increase for other crops is about 5%, with a maximum increase of about 8% in some districts [57]. The authors suggest also that shifting the planting date of *Boro* season crops, either earlier or later, is not helpful in reducing the projected increase in net irrigation requirements. Thus, adjusting the crop calendar might not be effective in adapting to climate change during the dry season in Bangladesh [57].

Projections of the likely impacts of climate change on irrigation requirements are particularly timely in Bangladesh, given the heavy reliance on groundwater for irrigating rice and other crops in the *Boro* season. Much of the country's success in achieving self sufficiency in rice production is due to a substantial increase in groundwater pumping for irrigation [56,57]. Much of the increasing demand for groundwater in recent years is due to the expansion of irrigated area and the intensification of agriculture during the *Boro* season, rather than changes in rainfall or evapotranspiration [58,59]. Given that net irrigation requirements are projected to increase by an average of just 3% to 5% for rice and other crops in the *Boro* season [57], it is possible that sustainable rates of groundwater pumping can be achieved in Bangladesh, although policy interventions might be required to reduce groundwater pumping in areas of notable overdraft, such as in the Barind and Madhupur Tracts and in Dhaka and nearby areas [58–60].

Unlike farmers in Bangladesh, rice farmers in Sri Lanka depend largely on rainfall and surface water supplies. Rice is produced on about 30% of the land area in Sri Lanka, and the activity directly supports about 800,000 farm families, most of whom cultivate less than 1 ha of land [61]. Farmers rely largely on inter-monsoonal and monsoon rains, thus placing them at substantial risk of crop failure in years when rainfall is limited or delayed [61]. Several authors have shown that rainfall in Sri Lanka declined during the latter half of the 20th century [62–64]. Domroes and Schaefer [65] suggest that the estimated average annual rainfall declined from 2005 mm during 1931 to 1960, to 1861 mm (7.2%) during 1961 to 1990. Annual rainfall varies notably across the country. The wet zone in Southwestern Sri Lanka receives about 2000 mm of rainfall, while the dry zone in northern and eastern Sri Lanka receives only 800 mm to 1200 mm of rainfall per year [61]. Water storage and irrigation are particularly important activities in the dry zone.

The average annual rainfall in Sri Lanka is projected to increase by 14% in 2050 in the SRES A2 climate change scenario and by 5% in the SRES B2 scenario [61]. However, average annual rainfall during the dry season is projected to decline by 17% and 9% in the A2 and B2 scenarios, respectively. The average wet season temperature is projected to increase by 1.6 °C and 1.3 °C in the two scenarios, causing evapotranspiration to increase by 2% and 1%, respectively [61]. The combination of higher temperatures and reduced rainfall will result in higher irrigation water requirements in the dry season. De Silva *et al.* [61] project increases in rice irrigation requirements of 23% and 13% in 2050 for the A2 and B2 scenarios. The largest proportional increase is projected for Batticaloa, in Eastern Sri Lanka (45% and 13% in the A2 and B2 scenarios), while a small reduction in irrigation requirements is projected for Hambantota, in southern Sri Lanka (−2% and −4% in the A2 and B2 scenarios). The projected reductions in average rainfall, in addition to projected shifts in the timing of the monsoon rains, and in combination with increases in evapotranspiration, will challenge rice producers, particularly in the dry zone. Earlier planting of rice and the use of shorter season varieties might be helpful in mitigating the potentially negative impacts [61]. In some areas of the country, it might become necessary to reduce the area planted in rice.

Elsewhere in Asia, climate change will increase average rainfall in South Korea by 25% to 53%, yet effective rainfall will increase by only 2% to 8%, resulting in a 1% to 8% reduction in rice irrigation requirements [66]. The ratio of available water resources to irrigation demands will increase accordingly, yet farmers and water agencies might consider investing in additional water storage, to mitigate water shortages in dry years. Wang *et al.* [67] project increases of 2% and 5% in rice irrigation requirements during 2046 to 2065 for the SR A1B and SR B1 climate change scenarios in southeastern China. The projected increases rise to more than 5% and 15% for 2081 to 2100 for the two scenarios, respectively. Ye *et al.* [68] project that rice water requirements will increase from an average of 700 mm during 1981 to 2000, to 1027 mm during 2011 to 2040, and to 1150 mm during 2071 to 2100. The primary cause of the increase in rice irrigation requirements is the increase in average temperature that characterizes the A1B climate change scenario. Chiang and Liu [69], in a simulation of the SRES A2 and SRES B2 scenarios, show that climate change might cause water shortages as large as 27%, 29%, and 31% of rice irrigation demand in southern Taiwan during the 2020s, 2050s, and 2080s, respectively, thus impacting rice output during the dry season. The impacts of the water shortages can be lessened, in part, by reducing planted area and minimizing conveyance losses in the irrigation system [69].

Kunimitsu *et al.* [70] examine the likely changes in rice productivity, due to climate change, across Japan. The authors determine that after the 2050s, climate change will increase rice yields in northern areas, such as Hokkaido and Tohoku, due largely to beneficial warming during the rice production season. By contrast, climate change will reduce rice yield and grain quality in other regions after the 2050s, while also increasing the variation in rice productivity. The authors suggest that much of the negative impact of climate change can be offset by transplanting rice earlier in the year, except in the southern region of Kyushu, provided that sufficient irrigation water will be available during April, as needed, to support an earlier transplanting schedule [70].

Naylor *et al.* [71] examine the potential impacts of climate change on rice production on the islands of Java and Bali, which generate about one-third and one-fifth of Indonesia's annual rice output, respectively. The authors suggest that the likelihood of a 30-day delay in the onset of the monsoon will increase with climate change, thus raising concern regarding food security and livelihoods in future. Rainfall likely will increase near the end of the crop year (April to June), while decreasing in the dry season (July to September). The authors recommend adaptation strategies that include greater investment in water storage, drought-tolerant crops, crop diversification, and early warning systems [71].

Indonesia already is susceptible to notable changes in annual rainfall associated with El Niño/Southern Oscillation (ENSO) events. Much of the rice production area in Indonesia is impacted by the warmer, drier conditions that prevail during El Niño years [72]. Impacts occur in both irrigated and non-irrigated settings, because the source of water for most of the irrigated rice production is a river, rather than a reservoir [73]. Only 800,000 ha of the 5.7 million ha of irrigated rice (14%) are served by a storage reservoir. The negative impacts of El Niño events on rice production are evident also in the Philippines, where an El Niño-induced drought caused a 24% reduction in rice output in 1998, which resulted in localized food shortages [74]. Investments in water storage, where feasible, might be helpful in reducing the negative impacts of drought on rice production in Indonesia, the Phillipines, and elsewhere.

Climate change will impact rice production in many coastal areas, due to increases in storm events in the near term and a rising sea level, over time [10,17]. Many farmers in coastal areas of Bangladesh already struggle to sustain rice production, as several cyclones have moved saline water inland in recent years, causing salinlity levels in rice fields to rise sharply to levels that impair crop production [75]. Storm surges and salinity intrusion threaten both rice production and aquaculture in coastal areas of Bangladesh, where millions of residents depend on these activities for their livelihoods and household food security [76].

The Government of Indonesia expects that by 2050, sea level rise will cause the area planted in rice to decline by 182,556 ha on Java and Bali, 78,701 ha on Sulawesi, 25,372 ha on Kalimantan, 3170 ha on Sumatra, and 2123 ha on Lombok [77]. Farmers in Indonesia currently plant about 13 million ha in rice each year and they produce about 68 million tons of rice [78]. Nearly all of the rice is consumed domestically, as exports account for less than one percent of production [78]. Rice contributes substantially to the country's food security, accounting for 48% of the average daily consumption of 2600 kcals per person, per day in Indonesia [78]. The country achieved rice self sufficiency in 2008 and the government plans to increase the area planted in rice and to intensify rice production methods, to maintain sufficient production in future [79,80].

2.3. Brown Planthoppers

Climate change also might create conditions in which some pests of rice, such as the brown planthopper, will thrive, and will cause more damage than in the past. Severe infestations of brown planthopper have become more frequent in recent years in Indonesia and other tropical countries, due largely to the excessive use of nitrogen fertilizer on hybrid rice varieties and the misguided use of insecticides that destroy beneficial predators [81–85]). The loss of biodiversity in regions where rice production dominates the landscape also contributes to higher rates of infestation, as there is less supportive habitat for beneficial predators [86]. The brown planthopper is a phloem sucking insect that causes damage directly, while also transmitting viral diseases, such as grassy stunt and ragged stunt [87,88].

Higher temperatures and elevated concentrations of CO_2 likely will impact the development and life cycles of brown planthoppers and other insect pests of rice and many crops. Shi *et al.* [88] show that higher temperatures, alone, accelerate nymphal development, while reducing the weight of the

F1 adults and their honeydew excretion. Elevated concentrations of CO_2 increased the lifespan of brachypterous females, at ambient temperatures, but had no impact on female longevity at higher temperatures. Female fecundity was higher at higher temperatures and at elevated concentrations of CO_2. Shi *et al.* [88] conclude that higher temperatures and higher levels of CO_2, considered together, might lead to larger populations of brown planthoppers.

Interventions to reduce farm-level application of insecticides, while also modifying seeding rates and nitrogen applications, have been helpful in reducing the damage from brown planthoppers in several countries. Huan *et al.* [89,90] and Heong *et al.* [91] report notable reduction in pesticide use among farmers in the Mekong Delta of Vietnam, in response to successful public education campaigns. Farmers adopting the recommended practices observed less damage from brown planthoppers and earned higher seasonal incomes, due largely to smaller expenditures on pesticides. Rice plants grown in hydroponic culture with high concentrations of silicon exhibited significant resistance to brown planthoppers, suggesting that silicon fertilizer might provide a useful, non-pesticide complement to chemical control efforts, particularly in the context of susceptible varieties [92]. Efforts to develop rice varieties that are resistant to brown planthoppers are underway, yet resistance likely should be regarded as just one component of an integrated management approach that includes wise use of fertilizer and insecticides [93].

3. Adapting to Climate Change

3.1. Farm-Level Adaptation

Farm-level adaptation efforts will vary with location and with the nature of the impacts observed. In some areas, farmers will respond to increasing variability in precipitation by investing in irrigation or enhancing efforts to capture and store rainfall. Investments in irrigation and rainwater capture are forms of adaptation that enable farmers to gain some control over the amount and timing of soil moisture available to plants, thus improving their resilience to the increased variation in rainfall due to climate change [94].

The most common form of farm-level adaptation to increasing water scarcity in the Rajshahi District of Bangladesh is greater use of groundwater for irrigation [95]. Other strategies include increasing the use of surface water and planting crops other than rice. Alauddin and Sarker [96] observed similar strategies in a survey involving 1800 farmers in several drought-prone and groundwater-depleted areas of Bangladesh. The four most preferred strategies for adapting to drought include planting shorter duration rice varieties, switching to non-rice crops in the dry season, applying more irrigation water in the dry season, and applying supplemental irrigation in the wet season [96]. Investments in irrigation in other countries also will be helpful in adapting to climate change, provided sufficient water resources are available [97].

Farmers in many areas will modify their crop choices and crop calendars, in response to changes in rainfall patterns and average temperatures. In some areas, climate-induced changes in the beginning and ending dates of the wet season will require that farmers modify rice planting and harvest dates, with potential implications for the number of crops produced each year, rice yields, and aggregate production [98]. Delays in planting might result in a shorter growing season and lower yields, while also possibly delaying the start of a subsequent season. Dharmarathna *et al.* [99] show that shifting the planting date for dry season rice forward by one month in the Kurunegala District of Sri Lanka will increase the average yield by 130 kg per ha, while delaying the planting date by one month will reduce the average yield by 170 kg per ha. Two-thirds of the rice farmers interviewed by Le Dang *et al.* [100] in the Mekong Delta of Vietnam report shifting their planting and harvest dates to accommodate changes in weather patterns. About 60% of the rice farmers modify their use of labor, while also changing the times at which they apply irrigation, fertilizer, and pesticides.

Farmers in Bangladesh also exhibit notable responsiveness to differences in seasonal rainfall and average temperatures. In lower rainfall areas, farmers prefer to cultivate irrigated rice in the dry season, while in higher rainfall areas, farmers prefer to grow rice during the wet season [101]. Farmers in low temperature zones prefer rainfed rice production in the wet season, while farmers in high temperature zones prefer irrigated rice production in the dry season. If climate change brings higher temperatures to Bangladesh, rainfed rice production might decline, while dry season rice production might increase [101].

Babel *et al.* [32] suggest that farmers in Thailand can increase rice yields by 23% to 34% by delaying the sowing date for rice by 20 to 30 days, to avoid high temperatures during the grain filling stage. In addition, advancing the date of nitrogen application by 10 days can improve crop yields. Changing the date of land preparation or modifying tillage practices, such as plowing and harrowing, had no significant impacts [32].

In a simulation study of the potential impacts of climate change in central Vietnam, Shrestha *et al.* [102] determine that the projected decrease in rice yields of 1% to 23% in the winter season can be offset by delaying the date of transplanting by one month and applying 100 mm of irrigation water in each of four events during the season. At present, winter rice production is largely rainfed in the region, although water for irrigation is available in perennial streams. Applying fertilizer in several doses, rather than a single dose, can increase rice yields by 1.8% to 5.1% [102].

Deb *et al.* [103] examine climate change scenarios and rice production in Ca Mau Province, in the Mekong Delta of Vietnam. They suggest that a delay in the date of transplanting will offset a portion of the expected decline in rice yields in the summer-autumn season, while an earlier date of transplanting will enhance rice yields in the autumn-winter season. In the summer-autumn season, a delay of 45 days is optimal, with regard to rice yields in 2025 and 2055. Delaying the date of transplanting by an additional 15 days in 2085 will further enhance rice yields in that year. These delays shift the weather-sensitive plant stages, such as flowering and reproduction, to periods with cooler temperatures and higher rainfall, thus increasing the likelihood of successful pollination and grain development. Advancing the date of transplanting in the autumn-winter season increases the likelihood of receiving sufficient rainfall during critical plant stages, while also minimizing the probability of chilling injury during anthesis and maturity [103].

Farmers in Cambodia also might offset some of the negative impacts of climate change by delaying rice planting. Chun *et al.* [94] suggest that a delay of 50 days beyond the baseline (for 1991 to 2000) planting date, in conjunction with an increase in nitrogen fertilizer application to 100 kg N per ha, might increase yield of the Sen Pidao cultivar by 20% in the 2080s, relative to the baseline yield. The authors suggest also that irrigation is essential to fully offset the potentially negative impacts of climate change in Cambodia, which arise largely due to projected increases in average temperatures [94]. Farmers in Central Vietnam also might offset the negative impacts of climate change by delaying the planting dates of winter season (rainfed) and summer season (irrigated) rice by about one month and three weeks, respectively [104]. Specific, optimal planting dates vary somewhat across scenarios representing climate change impacts in the 2020s, 2050s, and 2080s. Supplemental irrigation in the winter season also would be helpful in increasing rice yields.

In areas where water supplies become limited, farmers might need to modify their annual production program to include only one or two crops per year, rather than two or three. Where feasible, many farmers might increase their use of nitrogen fertilizer and irrigation to offset the potentially negative impacts of climate change [94,105]. Farmers also might consider changing crop calendars and the varieties of rice they produce, to optimize output in the shifted, and possibly shortened, rice growing seasons [7,106,107]. Changes in crops, cultivars, and crop calendars will modify the total costs and net returns in farming and the risks associated with crop production and marketing. Optimizing crop choices and production practices, in response to climate change, will require that farmers acquire new knowledge of production and marketing opportunities. They will also need timely and affordable access to weather forecasts and information regarding enhancements in drought and flood management practices, pest populations, and control measures [96,100,108].

3.2. Regional Adaptation Efforts

Many farmers, input supply firms, and marketing agents will need better information and enhanced training to adapt successfully to climate change [109,110]. The information and training programs might be provided by extension service personnel and by representatives of companies engaged in the production and sale of farm inputs, including irrigation equipment, pesticides, plant nutrients, and farm equipment. In some countries, substantial investments in agricultural extension services will be needed to assist farmers in learning how best to adapt to climate change. Participatory programs, such as the Farmer Field Schools introduced by the Food and Agriculture Organization in the 1980s, can be designed to increase farm-level capacity to gather and interpret local and regional information regarding weather, soil moisture, pest populations, nutrient status, and crop responses [111,112]. Adaptive research, in which farmers participate in evaluating proposed changes in production methods also has merit in determining and then disseminating recommendations that will advance adaptation efforts across large agricultural areas [113,114].

Given the uncertain and diverse nature of the impacts of climate change on rice production, regional adaptation efforts might begin with investments in field-level data collection, farmer training, and extension service programs. Stigter *et al.* [115] recommend investments in extension agrometeorology, which is largely an effort to increase the capacity of farmers to gather and interpret data describing weather conditions, with the goal of enhancing their understanding of the challenges posed by climate change [116,117]. Extension efforts in Indonesia include Climate Field Schools and Science Field Shops, in which farmers interact with scholars to gain insight regarding climate change, adaptation, and data collection methods that farmers can implement at the plot level [118–121].

Investments in regional irrigation and drainage schemes will be needed, where appropriate, to enhance the collection, storage, and distribution of irrigation water and to provide adequate drainage of agricultural lands [122–124]. Investments in flood control structures and flood risk management also will be needed in areas where climate change will increase the frequency and severity of floods [108,125,126]. Investments in education, training, and international exchange will be needed to promote optimization of systems that include irrigation, drainage, and flood control components [127,128]. Efforts should be made also to include farmers, business persons, and other residents in the planning process when designing infrastructure investments and developing operational protocols [129].

3.3. National and International Investments

Many of the high yielding varieties of rice that are produced currently across large areas of Asia were developed for their high yielding potential, rather than drought tolerance. Thus, much of the rice production in Asia, particularly in rainfed areas, is susceptible to substantial yield reductions in drought conditions [7,130,131]. The potential gains from developing drought-tolerant rice varieties are substantial, given the global importance of rice in assuring food security, particularly in Asia and in portions of Africa. Recent experience with drought-tolerant varieties in Asia suggests that the newer varieties generate somewhat higher yields in normal to good rainfall years, while providing some yield protection in moderate drought years [132]. However, in severe drought years, both conventional and drought-resistant varieties have failed to produce a viable crop. Further research and additional support from donors and national governments will be needed to develop better drought-resistant varieties and to achieve successful uptake by farmers [132].

National and international research centers already are engaged in efforts to develop new crop varieties that are tolerant of drought, higher temperatures, more variable rainfall, extended submergence, and salinity [11,12,14,133]. Success in developing such varieties will benefit farmers and consumers in many countries. Similar efforts are underway to develop new breeds of livestock that will be more tolerant of higher temperatures [134–137]. Research centers also are developing better methods of understanding the likely impacts of climate change on global and regional weather patterns [138–140]. Such efforts, which generate international public goods, will be helpful in developing better methods for predicting changes in weather on a timeframe that might be helpful to farmers and others engaged in agriculture.

Breeding efforts are underway also to identify salt tolerant rice cultivars that might be planted in coastal regions subject to saline intrusion, due partly to climate change [141]. Islam *et al.* [142] examine several rice varieties developed for use in the wet and dry seasons in the coastal region of Bangladesh. The authors recommend using varieties with higher salt tolerance and shorter duration in the dry season, while using salt tolerant varieties that are also tolerant of stagnant flooding conditions in the wet season. Indeed, the planting of salinity-tolerant rice varieties already is the primary adaptation response for farmers in coastal areas of Bangladesh, where major storms and sea level rise have caused soil and water salinity in rice fields to increase in recent years [75].

A similar strategy might be appropriate for coastal areas of the Mekong Delta in Vietnam, which also are subject to saline intrusion [143–146]. Scientists at the International Rice Research Institute and in several national research centers are developing flood-tolerant varieties with enhanced resistance to submergence [147,148]. Sarangi *et al.* [149] describe the higher productivity achieved with the new rice variety, Amal-Mana, in stagnant flooding conditions in trials conducted on farms and on experiment stations in West Bengal. In addition to producing higher yields, the quality of the grain is superior for cooking and eating, in comparison with traditional rice varieties [149]. Researchers with Kasetsart University and several rice research centers in Thailand have developed a new variety of rice (Hom Mali 821), which is tolerant of flash flooding, moderately resistant to brown planthoppers, and has excellent grain quality [150].

Chun *et al.* [94] suggest that national investments in agricultural infrastructure, such as irrigation and drainage systems, will be helpful in reducing the negative impacts of climate change on rice yields in Southeast Asia. The authors note, for example, that expanding irrigation schemes in Cambodia to provide service to a larger portion of the country's rice fields, would increase national agricultural productivity, while also enhancing farm-level adaptation to the changes in weather conditions that will accompany climate change. National governments and international donors are well placed also to invest in regional irrigation, drainage, and flood control facilities.

Provinical and national governments also might consider providing or promoting crop insurance for smallholder farmers. Although crop insurance will not modify the technical coefficients that describe the farm-level damage from climate change, it can enable farmers to sustain financial losses with greater likelihood, while also enabling them to invest in new crop varieties and production methods that will enhance their resilience to climate change. Over time, private markets in crop insurance should arise in some settings, although some degree of public oversight might be required to ensure that smallholder farmers can participate successfully in the insurance market. Research will be needed also to determine the best form of insurance to implement in regions where damaging floods might occur with increasing frequency. The compensation payments for damages claimed by farmers holding indemnity policies might easily exceed the premiums paid in some years, particularly if the premiums are subsidized by a government agency [151]. Weather index insurance might be preferable to indemnity insurance in some areas.

The Government of Japan has provided compulsory crop insurance for all of the country's rice farmers for many years [152]. Payments are made to farmers in years when average rice yields are smaller than pre-determined standard yields, which vary by prefecture. Iizumi *et al.* [152] examined the likely impact of climate change on rice yields and insurance payments in Japan, using downscaled climate change projections for each prefecture to simulate temperature effects, while also accounting for the likely impacts of storms, diseases, and pests. The authors project a 10% increase in rice yields in the 2070s in Hokkaido, in Northern Japan, due to a significant reduction in damage from cool summer temperatures. Rice yields will decline in the 2070s in Central and Western Japan, due to an increase in heat stress and a reduction in biomass, due to a shortening of the growth period [152]. The authors also project changes in the standard yields that determine the insurance payment benchmarks. Those yields will be higher in the 2070s in Hokkaido and Tokai, where average yields also will increase, but lower in all other areas. The resulting simulated insurance payouts are smaller in the 2070s than in the 1990s, in six of the nine regions defined by Iizumi *et al.* [152] in their analysis. In sum, the annual payout for the national rice insurance program is 13% smaller in the 2070s than in the 1990s (104.4 billion yen *vs*. 120.2 billion yen). The authors suggest that adaptation measures, such as changing the planting date or adopting new cultivars, might further reduce the average annual insurance payout [152].

4. Reducing Methane Emissions

Flooded rice paddies have been known to be a major source of methane and nitrous oxide, both of which are important atmospheric pollutants, for many years [153–160]). Methane, carbon dioxide, and nitrous oxide contribute an estimated 87% of total radiative forcing, thus having a notable impact on global warming [161]. Methane is generated in the anaerobic conditions that prevail in flooded rice paddies. Rice production in upland areas, in which the fields are not maintained in flooded conditions, generates substantially less methane per hectare and per unit of rice [162,163].

Changes in soil and water management practices can substantially reduce methane emissions attributed to paddy rice production [164–167]). Among the major cereals, rice production generates higher methane emissions per hectare and per unit of yield than does the production of wheat or maize [168]. The potential reductions in annual methane emissions through improvements in soil and water management are particularly large in areas where two or three crops of rice are produced each year [169].

Methane emissions from rice paddies and other wetland ecosystems likely will increase with climate change, as the increasing atmospheric concentration of CO_2 promotes greater root development per unit of biomass produced [170,171]. As rice plants allocate a larger portion of assimilated carbon to roots, the amount of carbon available to methanogenic Archaea in the soil will increase, thus leading to greater generation of methane per unit of rice production [170,171]. Thus, efforts to reduce methane emissions from rice paddies are needed to offset both the necessary increase in rice production to sustain global food security and the CO_2-induced increase in methane generation per unit of wetland area [170,171].

4.1. Intermittent Drainage vs. Continuous Flooding

Methane generation and release from rice production can be reduced by switching from continuously flooded paddies to a program of intermittent irrigation and drainage, and by limiting the amount of plant residue incorporated into soils after harvest and before planting [172,173]. Small reductions in the time during which rice paddies are inundated can substantially reduce methane emissions. However, switching from anaerobic to aerobic production can create the conditions that support nitrification and denitrification, such that nitrous oxide emissions can increase with the change in water management strategy [174,175]. The degree to which methane emissions are reduced and nitrous oxide emissions are increased is largely an empirical issue, which is influenced by soil characteristics and the history of soil and water management in a given location [176]. The timing of irrigation and drainage events in rice paddies also can influence methane and nitrous oxide emissions, while also impacting rice yields [174].

Farmers in Japan have been draining their rice fields in midseason for many years, largely to increase crop yields, by enabling the aeration of roots and by minimizing the excessive growth of ineffective tillers [177]. Following the midseason drainage period, which is about seven to ten days in length, many farmers also practice intermittent irrigation and drainage for the remainder of the season [178,179]. That practice allows for continued root development, while also preventing roots from rotting. In addition, intermittent irrigation and drainage requires less irrigation water than the volume required to maintain continuous flooding [177,180]. The enhanced root development also reduces the likelihood of rice plants lodging, as harvest approaches.

The midseason drainage and the subsequent, intermittent irrigation and drainage practiced by Japanese rice farmers have been shown to reduce methane emissions. Yagi *et al.* [181] observed reductions in methane emissions of 42% and 45% in 1991 and 1993, respectively, on experimental plots in Kanto Province, Japan, that were drained at least two times during the season. Intermittent drainage was applied twice in 1991 and eleven times in 1993. The authors suggest that the latter program of eleven intermittent drainage events reflects conventional Japanese rice cultivation in the region. There were no significant differences in nitrous oxide emissions or rice yields on the continuously flooded and intermittently drained plots in either year [181]. The authors conclude that water management can be an important methane mitigation measure, provided that rainfall is not excessive and farmers have adequate control of irrigation water deliveries.

Tyagi *et al.* [182] examined the impacts of midseason and intermittent drainage on methane emissions from rice fields on an experiment station in Lucknow, India, where farmers typically drain their rice paddies once each season, at the tillering stage, to provide oxygen to the roots. The authors compared that practice with continuous flooding, midseason drainage at 70 days after planting, and intermittent drainage involving two drainage events at 21 days and 77 days after planting. The observed seasonal methane effluxes from the plots were 347, 315, 291, and 205 mg CH_4 per m^2 per day, for the continuous flooding, tillering stage drainage, midseason drainage, and intermittent drainage treatments, respectively. In comparison with continuous flooding, seasonal methane emissions were reduced by 9%, 37%, and 41%, respectively, with the selected drainage treatments [182].

Installing subsurface drains beneath rice fields also will aid in reducing methane emissions, particularly in poorly drained areas. Subsurface drains speed the drying process of soils beneath rice fields, thus allowing more oxygen in the root zone and suppressing methanogenic activity [183]. In the 1960s, the Government of Japan implemented a program of land consolidation and investment in infrastructure to increase rice production and enhance national food security. Within that program, subsurface drainage systems were installed beneath many poorly drained rice fields across Japan [183,184]. As a result, many rice fields in Japan are equipped with subsurface drainage systems.

Shiratori *et al.* [183], examined the impacts of a subsurface drainage system on methane emissions in a study involving two rice fields in Niigata Prefecture, where 80% of the rice fields improved since the 1960s are served by subsurface drains. Methane emissions on the drained field were 71% less than emissions from the non-drained field. In a similar study involving three pairs of rice fields, also in Niigata Prefecture, Furukawa *et al.* [184] found that the methane generation potential of drained soils is about 40% less than the methane generation potential on fields without subsurface drains.

Farmers in China also have adopted the practice of draining their rice fields during the season, primarily to increase yields. The practice of midseason drainage first appeared in Northern China in the early 1980s, and has since replaced continuous flooding over much of the country's rice production area [185,186]. In a simulation exercise using the DNDC (DeNitrification-DeComposition) biogeochemical model, Li *et al.* [185] project that the methane emissions from all of China's paddy rice fields in 1990 might have been within the range of 8.6 to 16.0 Tg CH_4 per year, if the fields had been continuously flooded. If the fields had all been drained at midseason, the methane emissions might have been in the range of 2.3 to 10.5 Tg CH_4 per year. For the period of 1980 through 2000, the authors project that methane emissions from all of China's paddy rice fields were reduced by 40% (about 5 Tg CH_4 per year), due to the widespread adoption of midseason drainage [185]. For perspective, the estimated methane emissions from all rice fields, globally, during 2000 to 2009, are within the range of 33 to 40 Tg CH_4 per year [187]. Thus, the adoption of midseason drainage by paddy rice farmers in China might have reduced global emissions of methane from rice fields by about 12% during the decade of 2000 to 2009.

Methane emissions might be reduced further on rice fields cultivated in aerobic conditions throughout the season. Aerobic rice production, which is known also as upland rice production in many settings, is characterized by non-flooded, non-puddled, and non-saturated soil conditions [188]. Rice varieties with drought-resistant, high-yielding characteristics have been developed for use in aerobic production [189–192]. Xue *et al.* [193] examined alternative irrigation and nitrogen treatments on experimental plots of the aerobic rice variety HD297, in a two-year study conducted near Beijing in 2003 through 2004. Irrigation treatments varied by the amount of water applied before and after panicle initiation. Average grain yields on the plots receiving the most irrigation before and after panicle initiation ranged from 2.4 to 4.1 t per ha in 2003 and from 4.8 to 5.7 t per ha in 2004. Average grain yields on the plots receiving the most irrigation before panicle initiation, but less irrigation later in the season, ranged from 0.8 to 2.5 t per ha in 2003 and from 5.1 to 5.6 t per ha in 2004. The higher yields in 2004 might be due to more favorable weather conditions, including a more even distribution of rainfall, higher levels of solar radiation, and lower night temperatures than those that were observed in 2003 [193]. Although the authors did not measure methane emissions, the yields obtained in 2004 suggest that aerobic rice production might be a viable alternative to flooded paddy production in some settings.

In a three-year experiment conducted in southeastern Uruguay, with an *indica* rice cultivar, Tarlera *et al.* [194] compared the methane and nitrous oxide emissions on rice fields that were flooded continuously from 30 days after emergence (CF30), with fields that were irrigated intermittently from 30 days after emergence through 70 days after emergence (AWDI). The second set of fields was then flooded continuously for the remainder of the season. The mean seasonal methane emissions from the CF30 plots were 208, 249, and 249 kg CH_4 per ha, during each of three crop seasons. The mean seasonal emissions from the AWDI plots were 93, 106, and 96 kg CH_4 per ha, respectively. The differences in the means are statistically significant in years two and three. The mean seasonal emissions of nitrous oxide range from 0.3 to 1.9 kg N_2O per ha, across treatments and years. None of the differences in N_2O emissions is statistically significant.

The notable reductions in methane emissions, achieved by modifying the irrigation strategy, are associated with reductions in crop yields. In particular, the mean rice yields on the CF30 plots were 11,171, 10,387, and 9803 kg per ha, during each of three crop seasons, while the mean seasonal yields on the AWDI plots were 10,170, 8700, and 8992 kg per ha, respectively [194]. The reductions in the mean yields are statistically significant in years two and three. The authors suggest that the reductions in crop yields might be due partly to the particular irrigation treatment, in which water is applied only when 50% of the available soil moisture has been removed. An alternate wetting-and-drying strategy involving more frequent irrigation might generate meaningful reductions in methane without significantly reducing crop yields.

Wang *et al.* [164] also examine the potential reduction in methane emissions when modifying the irrigation strategy, in an experimental setting in Nanjing, China. The authors compare emissions from continuously flooded fields (W0), with emissions from fields that are drained twice each season: once for nine days at mid-season, and again for two weeks before harvest (W2). The authors also examine the potential impacts of supplemental nitrogen and the incorporation of rice straw into the soil before transplanting. The mean seasonal methane emissions in 2006 from the W0 and W2 plots were 390 kg CH_4 per ha and 156 kg CH_4 per ha, respectively. The mean emissions from the plots without (S0) and with (S1) straw incorporation were 159 kg CH_4 per ha and 387 kg CH_4 per ha, respectively. Thus, modifying the irrigation strategy reduced seasonal methane emission by about 60%, while the incorporation of straw increased methane emission by 59%. The authors conclude that water management and straw incorporation are equally important factors in determining methane emissions from rice paddies [164].

The irrigation strategy and straw incorporation had no significant impacts on rice yields in the Wang *et al.* [164] study. By contrast, supplemental nitrogen significantly increased grain yield and straw biomass, while having no impact on methane emissions. Also of interest, any increases in N_2O emissions that might have been caused by the supplemental nitrogen application of 220 kg N per ha, per crop (N1), were much smaller than the reductions in CH_4 emissions achieved by modifying the irrigation strategy, on a carbon dioxide equivalent basis. In particular, the mean reduction in CH_4 emissions, across combinations of the S0, S1, N0 (no supplemental nitrogen), and N1 treatments is about 5869 kg CO_2-equivalents per ha, while the mean increase in N_2O emissions is about 24 kg CO_2-equivalents per ha [164]. Thus, it might be possible to offset some of the potential yield reduction due to modifying the water management program by applying supplemental nitrogen, without substantially increasing nitrous oxide emissions, on a CO_2-equivalent basis.

About 40% of China's rice production area is found in the middle reaches of the Yangtze River, where many farmers cultivate paddy rice in rotation with rapeseed. Xu *et al.* [195] examine the implications of alternative water management practices on methane generation during the rice production season and also during the subsequent rapeseed production season. The authors compare continuous flooding of rice paddies (CF) with initial flooding and intermittent wetting and drying (FWI), and with initial flooding and only limited irrigation during drought conditions and when fertilizer is applied (RFL). In the RFL treatment, the rice plants rely largely on rainfall. Both the FWI and RFL irrigation methods reduced methane emissions during the rice season, while increasing the emissions of nitrous oxide and carbon dioxide. Water management strategies in the subsequent rapeseed season further reduced emissions of methane and nitrous oxide on the FWI and RFL plots, while having no further impact on carbon dioxide emissions. Thus, the FWI and RFL treatments generated significant reductions in annual global warming potential, when considering the full cycle of the rice-rapeseed rotation [195].

Pandey *et al.* [196] compare methane and nitrous oxide emissions on rice fields irrigated intermittently (AWD) with emissions on continuously flooded fields (PF), in a single-season experiment in Hanoi, Vietnam. The authors also examine the potential impacts of several soil amendments, including animal manure, aerobically composted rice straw, and biochar produced from rice straw. The AWD plots were continuously flooded for 24 days after transplanting. Irrigation was then discontinued until moisture receded to a depth of 15 cm below the soil surface. At that time, irrigation was applied to achieve a 3 to 7 cm water level above the soil surface. This cycle of wetting and drying was continued until 15 days before harvest, with the exception of continuous flooding during the flowering stage, which occurred from 62 to 76 days after transplanting. In sum, three irrigations were applied on the AWD plots, at 37, 48, and 58 days after transplanting.

Statistically significant reductions in methane emissions and significant increases in nitrous oxide emissions were observed on the AWD plots, largely across the soil amendment treatments [196]. The mean annual methane emissions ranged from 108 to 353 kg CH_4 per ha on the PF plots, while declining to a range of 31 to 105 kg CH_4 per ha on the AWD plots. The mean annual nitrous oxide emissions ranged from 0.27 to 0.44 kg N_2O per ha on the PF plots, while increasing to a range of 0.67 to 0.97 kg N_2O per ha on the AWD plots. Methane emissions were lowest on plots with no soil amendments, followed by those amended with biochar. Animal manure and composted straw generated higher methane emissions on both the PF and AWD plots.

There were no significant yield effects due to any of the treatments in the Pandey *et al.* [196] study. Mean rice yields ranged from 5250 to 6020 kg per ha. As in the results reported by Wang *et al.* [164], the increase in nitrous oxide emissions due to the change in irrigation strategy was much smaller than the reduction in methane emissions, on a CO_2-equivalent basis. Thus, the global warming potential of rice production was significantly reduced by switching from continuous flooding to intermittent irrigation in the Pandey *et al.* [196] study, both on a per hectare basis and per unit of rice yield. In particular, the estimated global warming potential ranged from 2784 to 8956 kg CO_2-equivalents per ha for the PF treatments, while declining to a range of 1005 to 2911 kg CO_2-equivalents per ha for the AWD treatments. Similarly, the global warming potential ranged from 510 to 1490 kg CO_2-equivalents per ton of rice for the PF treatments, while declining to a range of 197 to 544 kg CO_2-equivalents per ton for the AWD treatments.

4.2. Soil Amendments and Tillage

Methane is formed in rice paddies as methanogens (anaerobic Archaea) decompose carbonaceous materials in the soil. Thus, carbon sources, such as animal manure, rice straw, and other plant residues enhance methane generation in rice paddies [197–199]). In some deltaic areas, many farmers produce two or three crops of rice per year, often relying on irrigation to support the second and third crops.

Soil and water management of the rice fields, between crops, can be helpful in reducing methane releases during the subsequent rice season. Sander *et al.* [200] examined water management and tillage treatments between the wet and dry season rice crops on an experiment station in Los Baños, Philippines. The treatments included continuous soil flooding (flooded), soil drying by excluding rainfall (dry), and soil drying, with two tillage events (dry + tillage). The authors also examined the effects of incorporating or removing the plant biomass after harvest.

Methane emissions were significantly higher in the second season on fields with incorporated residue, than on fields from which the residue had been removed. Methane emissions were higher also on fields that were flooded during the fallow period, than on fields that were kept dry or were dried and tilled. Cumulative methane emissions, averaged over all fallow management treatments, were about twice as large on the fields with incorporated residue, than on those from which the residue had been removed [200]. The sum of methane emissions across both seasons was smaller for the dry and dry + tillage treatments, than for the flooded treatment. Nitrous oxide emissions were small in both seasons, and were not influenced by the flooding or tillage treatments. Rice yields were higher in the dry season than in the wet season. Yields were not influenced by soil and water management during the fallow period. In sum, maintaining rice fields in dry condition and removing plant biomass reduced methane emissions in the subsequent season. Further study is needed to determine the longer-term impacts of removing the plant biomass, which is an important source of carbon and potassium [200].

Ly *et al.* [201] examined the potential impacts of replacing rice straw with biochar, as a helpful soil amendment, in a controlled environment growth chamber study using soil from a rice production area in Cambodia. The authors also compared continuous flooding with a strategy of alternate wetting and drying. Supplemental nitrogen in mineral fertilizer was added in all treatments. Methane emissions were highest on plots treated with rice straw, followed by those treated with biochar. The lowest methane emissions were observed on plots with no soil amendment. On the soil amended plots, methane emissions were lower with alternate wetting and drying, than with continuous flooding. Methane emissions were higher with alternate wetting and drying, than with continuous flooding, on the treatments with no soil amendment. Nitrous oxide emissions were largely non-detectable during the experiment, when applying nitrogen fertilizer. Rice yields were slightly higher in the alternative wetting and drying treatments [201].

Pratiwi and Shinogi [202] also have examined the use of biochar to reduce methane emissions in rice production. In an outdoor pot experiment with two application rates, methane emissions were reduced by 45% and 55% when biochar was applied at the rates of 2% and 4% of the weight of soil in the pots. Mohammadi *et al.* [203] compared conventional residue management on rice fields (System A) with the practice of applying biochar to the fields (System B). The biochar was created by collecting the rice straw, rather than burning it in the field, and pyrolysing the straw with wood in an updraft oven. Rice husks were collected after milling, and were processed with wood in a pyrolitic cook-stove. The estimated carbon footprints of the rice produced in System A were 1.49 and 4.50 kg CO_2-equivalents for the spring and summer seasons, respectively. Most of the carbon footprint (87% in spring and 94% in summer) was comprised of methane emissions. By comparison, the estimated carbon footprints of the rice produced in System B were 49% and 38% smaller than those observed in System A. The smaller carbon footprints were attributed largely to stabilization of carbon in the biochar and reductions in methane emissions [203].

While incorporating plant residue in rice paddy soils generally increases methane generation, incorporation of selected portions of plant residue might provide agronomic benefits, while not increasing methane emissions. Penido *et al.* [204] examined the incorporation of fresh rice straw (FS), fresh rice husk (FH), rice straw ash (RSA), and rice husk ash (RHA), at the rate of 1% of the weight of soil, in a flooded pot experiment. Soils amended with the fresh materials (FS and FH) had higher levels of dissolved silicon than those amended with the ash materials (RSA and RHA), while the FS-amended soil had the highest concentrations of arsenic, iron, and methane. The authors conclude that amending soils with FH, RSA, or RHA might enable smallholder rice farmers to increase plant-available silicon, while not causing higher levels of methane emissions [204]. Although silicon is not considered an essential element, it has been shown to reduce biotic and abiotic stresses, including arsenic uptake and toxicity [205–214].

Sui *et al.* [215] examined the use of biochar created from rice straw in a two-year experiment on continuously flooded rice paddies at the Shenyang Agricultural University in Liaoning Province, China. Treatments included rice straw applied at 5.05 t per ha (S), and biochar applied at the rates of 1.78 t per ha (B1), 14.8 t per ha (B2), and 29.6 t per ha (B3). Control plots received no straw or biochar as a soil amendment. The authors also examined two rates of nitrogen fertilizer: 0 kg N per ha (N0) and 210 kg N per ha (N1). Total methane emissions were highest on the plots receiving straw at 5.05 t per ha. The biochar amendments reduced methane emissions, relative to the straw treatment, for both levels of nitrogen. Biochar also increased total soil carbon at higher rates than returning straw to the soil. The carbon in biochar can exist in soils over long time scales, and biochar increases soil porosity, while reducing soil bulk density [216].

Changing the cropping pattern from continuous paddy rice to paddy rice followed by maize or aerobic rice production can substantially reduce methane emissions. Weller *et al.* [217] examined methane and nitrous oxide emissions from three cropping patterns on experimental plots in Los Baños, Philippines. Replacing the second paddy rice crop with an upland crop (maize or aerobic rice) reduced methane emissions by 66% to 81%. Methane emissions were reduced also in the subsequent wet season, when paddy rice was again planted, by 54% to 60%. Annual emissions of nitrous oxide increased with the planting of an upland crop, yet the substantial reductions in methane emissions resulted in a smaller global warming potential with the diversified cropping pattern [217].

Zhang *et al.* [218] also examine methane and carbon dioxide emissions from fields planted in a rice-rapeseed rotation in Central China. The authors assess the implications of alternative tillage practices and of incorporating plant residue into the soil, following harvest. Returning plant residue to the field increased rice grain yields by 38% and 32% on plots receiving 3000 kg per ha and 6000 kg per ha of plant residue, respectively. Tillage practices did not influence rice yields, but they did have an impact on methane and carbon dioxide emissions. In particular, yield-adjusted emissions of methane and carbon dioxide, expressed as kg of CO_2-equivalents per kg of rice grain yield, were reduced by 16% on non-tilled plots, in comparison with conventional tillage. Returning 3000 kg per ha or 6000 kg per ha of plant residue did not influence methane and carbon dioxide emissions. Across all treatments, the combination of non-tillage and returning 3000 kg per ha of plant residue generated a relatively large, average rice yield (7325 kg per ha), with the lowest observed values of yield-adjusted methane and carbon dioxide emissions [218].

4.3. Direct Seeding vs. Transplanting

Most of Asia's rice fields are started by transplanting seedlings into puddled soil on land that has been prepared with wet tillage [219]. Puddling facilitates easy seedling establishment, but transplanting into flooded soils requires large volumes of water and substantial labor. In areas with increasing scarcity of both labor and water, direct seeding of rice, as an alternative to puddled transplanting, has gained favor among rice farmers [219,220]. Direct seeding into either wet or dry soil has the potential also to reduce methane emissions, as the rice paddies are flooded for a shorter period, than when transplanting into puddled fields. Kumar and Ladha [219] review many studies in which the methane emissions from direct seeded fields are compared with those from puddled, transplanted fields. In comparison with puddled transplanting on fields cultivated with continuous flooding, direct seeding into dry soils reduced methane emissions by 24% to 79%, while direct seeding into wet soils reduced methane emissions by 8% to 22%. Although nitrous oxide emissions increase with direct seeding into dry soils, the global warming potential tends to be lower for that method than for puddled transplanting, given the large reduction in methane emissions achieved with direct seeding [219].

Pathak *et al.* [221] measured the methane and nitrous oxide emissions from direct seeded (DSR) and transplanted (TPR) rice on nine experimental plots in the Jalandhar District of Punjab, India in 2009 and 2010. The TPR plots were continuously submerged during the season, at a depth of about 4 cm, while the DSR plots were submerged only on the days when irrigation was provided. The TPR plots received 21 to 22 and 15 to 16 irrigations in 2009 and 2010, respectively, while the DSR plots received 14 to 16 irrigations in 2009 and 12 to 13 irrigations in 2010. The smaller numbers of irrigations in 2010 reflect the more uniform distribution of rainfall received in that year. Methane emissions from the DSR plots ranged from 0.6 to 1.5 kg per ha in 2009 and from 4.2 to 4.9 kg per ha in 2010, while methane emissions on the TPR plots ranged from 42.4 to 57.8 kg per ha in 2009 and 56.0 to 56.5 kg per ha in 2010. Nitrous oxide emissions were similar on the DSR and TPR plots, ranging from 0.9 to 2.2 kg per ha, across treatments and years. Rice yields and yield attributes also were similar across treatments, while labor use and tractor hours were reduced by about 50% on the DSR plots [221].

Direct seeding of rice has been practiced for many years in the Mekong Delta of Vietnam, where farmers appreciate the smaller labor requirement, the shorter time required to establish the rice crop, and the smaller water requirement, in comparison with transplanting seedlings from a nursery [222]. In a survey of 102 farm households in three districts of Can Tho Province, participants reported grain yields ranging from 6270 to 7310 kg per ha in 2012 and from 6790 to 8850 kg per ha in 2013, with profits ranging from USD 658 to 1184 per ha in 2012 and from USD 758 to 1268 per ha in 2013, on direct seeded rice fields [222]. Managing weeds is a time consuming and costly effort when seeding the fields directly, but the yields and profits reported in the survey are among the highest observed in Asian rice production settings [222]. Weed management strategies include manual and mechanical weeding, the use of herbicides, and rotating herbicides with manual or mechanical weeding [223]. Adjustments in row spacing and in the timing of weeding operations also can influence weed growth and rice yields [224]. Using weed-free rice seeds and clean machinery also are essential practices when directly seeding rice fields [225].

Direct seeding of rice has been practiced in Sri Lanka since the 12th century [226]. Transplanting gained some popularity in the 1960s, when farmers gained access to transplanting technology, but most farmers have since resumed their reliance on direct seeding. In 2008, more than 95% of Sri Lanka's rice fields were direct seeded [226]. Most of the 202 farmers interviewed by Weerakoon *et al.* [226] practice wet seeding, in which pre-germinated seeds are broadcast on puddled, leveled fields that are free from standing water. In areas where water availability is limited or when initial rains are delayed, farmers practice dry land preparation. More than 90% of the farmers who use direct seeding describe the savings in time, labor, and expenditures, in comparison with transplanting, as desirable aspects of the program. As in other countries, weed control is a primary concern of farmers using direct seeding in Sri Lanka [226,227].

Farmers in the Indian state of Punjab also have used direct seeding for several centuries, yet the practice of transplanting rice gained popularity during the Green Revolution [228]. As in Sri Lanka, many farmers in Punjab have returned to direct seeding in recent years, due largely to the increasing cost of transplanting rice, as a result of increasing scarcity of water and labor. Most of the 320 farmers interviewed by Mahajan *et al.* [228], across all of six of the Punjab's agro-climatic zones, report using either a pre-emergent or post-emergent herbicide to control weeds. However, about 60% of those farmers report using inadequate water when preparing herbicide applications and using incorrect nozzles when applying the material. Thus, 42% of the farmers report weeding their fields manually, in addition to using herbicides for weed control [228]. As in other countries, weed management is the primary obstacle to achieving and sustaining high yields when direct seeding rice in Punjab.

4.4. System of Rice Intensification

The system of rice intensification (SRI) was introduced in the 1990s as a set of ideas regarding soil, water, and nutrient management designed to generate higher rice yields with fewer inputs [229–231]. In particular, SRI production strategies generally involve fewer rice plants per hectare, less irrigation water applied, and the use of inorganic fertilizer, such as animal manure [232]. One notable feature of SRI production is the switch from anaerobic to aerobic conditions, in which the soil is oxygenated for longer periods than when rice is produced in flooded paddies. The oxygen, in combination with the inorganic fertilizer, enhances the activity of soil biota, thus promoting stronger root development and healthier rice plants, resulting in higher yields per hectare in some cases [233,234]. The aerobic characteristic of SRI production is consistent with efforts to reduce methane emissions. Widespread switching from anaerobic to aerobic rice production might greatly reduce aggregate methane generation in some regions. However, the farm-level economics of SRI production must be positive, to support widespread adoption [235].

Ly *et al.* [236] compare rice yields and methane emissions on fields managed in conventional fashion (CMP) and those managed in accordance with the system of rice intensification (SRI) in a farmer field trial in a rainfed, lowland rice production area in Cambodia, during the wet season. In the SRI treatments, the rice paddies were kept saturated for two weeks after transplanting, followed by alternate wetting and drying. The authors also compared the use of mineral fertilizer with the use of animal manure, which is the preferred form of soil amendment in the SRI strategy. The treatments included animal manure alone (FYM), mineral fertilizer alone (MF), and the combination of both materials (FYM + MF).

The largest methane emissions were observed on the FYM + MF plots, under both the CMP (282 kg CH_4 per ha) and SRI (213 kg CH_4 per ha) regimes. Methane emissions generally were lower on the SRI plots than on the CMP plots, across the fertilizer treatments. Reductions ranged from 17% on the MF plots to 24% on the FYM + MF plots. There was no impact of water management practices on the non-fertilized control. Nitrous oxide emissions were below detection limits on all treatments, and there were no significant yield effects. Thus, the practice of SRI, in combination with mineral fertilizer, might be helpful in reducing methane emissions, while not increasing nitrous oxide emissions or reducing rice yields, in rainfed, lowland areas of Cambodia.

Jain *et al.* [237] examined the impacts of SRI and a modified version of SRI on methane and nitrous oxide emissions in a field study conducted at the Indian Agricultural Research Institute in New Delhi, in 2009. The treatments differed by the method of transplanting and the frequency of irrigation events. In the conventional transplanting treatment (TPR), two to three 30-day old seedlings were planted per hill, at a spacing of 15 by 20 cm. In the SRI and modified SRI treatments (MSRI), one seedling was planted per hill, at a spacing of 25 by 25 cm. Seedling age was 12 days in the SRI treatment and 18 days in the MSRI treatment. The TPR plots were irrigated every second day, with 5 cm of water, to maintain saturated moisture conditions. The SRI and MSRI plots were irrigated twice per week, with 3.5 cm of water, to maintain adequate moisture conditions. Seasonal methane emissions were 61% and 64% less on the SRI and MSRI plots, respectively, than on the TPR plots. Seasonal nitrous oxide emissions increased by an average of 23% on the SRI and MSRI plots, yet the global warming potential was reduced by 28% and 30% on the SRI and MSRI plots, respectively. Grain yields were reduced by 4.4% and 2.2% on the SRI and MSRI plots, but the reductions were not statistically significant [237].

Suryavanshi *et al.* [238] conducted a similar experiment, also at the Indian Agricultural Research Institute in New Delhi, during the rainy season of 2010. Conventional transplanting of 21-day old seedlings was compared with SRI production of 12-day old seedlings. The seasonal methane emissions were 32.3 and 19.9 kg CH_4 per ha for the conventional and SRI production methods, respectively. The estimated global warming potentials were 807.5 and 498.2 kg CO_2-equivalents per ha, while the average grain yields were 4530 and 5030 kg per ha, respectively. Thus, the SRI plots produced a significantly higher grain yield, while reducing the global warming potential by about 38%. The conventional plots received 18 irrigations (1170 mm), while the SRI plots received 12 irrigations (850 mm) [238].

5. Reducing Arsenic Uptake

Arsenic occurs naturally in soils and aquifers in many areas of the world [239,240]. In some areas, and in some agricultural settings, the concentrations of arsenic in soils and groundwater pose a substantial risk to human health [241,242]. Arsenic has been known to cause cancer in humans since the late 19th century. Early evidence pertained to the inhalation of arsenic, while evidence regarding cancer due to arsenic in drinking water appeared in the 1930s [243]. In the 1960s, arsenic was cited as a possible cause of lung and urinary tract cancers in Argentina [243]. Reports of skin lesions and hepatomegaly due to persistent use of drinking water with high concentrations of arsenic in West Bengal appeared in the 1980s [244,245]. In more recent years, several authors have described health effects including skin lesions, respiratory disease, impaired cognition, and cancer due to arsenic exposure in Bangladesh and other countries [241,246–249]).

The concentration of arsenic in much of the water drawn from shallow wells in Bangladesh exceeds the World Health Organization drinking water standard of 10 μg per liter [245,250,251]. Given the prevalence of shallow wells in Bangladesh and other countries of South and Southeast Asia, an estimated 50 to 100 million persons are at risk of drinking water contaminated with arsenic [252–254]. Acharyya and Shah [255] report that 9.5 million persons have been affected by high concentrations of arsenic in drinking water in nine districts in southern West Bengal. Based on an extensive, 14-year study of tubewells in Bangladesh, Chakraborti *et al.* [256] suggest that as many as 36 million and 22 million residents might be drinking water from wells with arsenic concentrations in excess of 10 μg per liter and 50 μg per liter, respectively. The latter concentration is the current national drinking water standard for arsenic in Bangladesh, which several authors suggest is not sufficiently restrictive [257–259].

5.1. Extent of the Problem

Arsenic is found in soils and groundwater across large portions of the major river deltas in South and Southeast Asia. To date, arsenic contaminated groundwater has been found in Bangladesh, India (West Bengal), Cambodia, Myanmar, and Vietnam [260]. The original source of the arsenic is the Himalayan mountain range, where arsenic-laden rocks have weathered and eroded, over thousands of years, thus releasing arsenic into the major river systems, including the Ganges-Brahmaputra, Irrawaddy, Chao Phraya, Mekong, and Red [260]. The development of irrigation in the river deltas has caused the mixing of arsenic between shallow and deeper aquifers, while also increasing the load of arsenic in agricultural soils [260,261].

Within the lower Mekong region, notable areas with elevated concentrations of arsenic in groundwater have been reported in Cambodia and Vietnam, while too few data are available to characterize the arsenic situation in Laos and Myanmar [262–267]. In Thailand, there is little evidence of naturally occurring arsenic in groundwater, but some areas are impacted by arsenic from mining operations [265]. Sampson *et al.* [268] suggest that as many as 100,000 persons are at high risk of arsenic exposure in Kandal Province, Cambodia, where arsenic concentrations in tubewells are particularly high [269–271]). All of the 46 wells examined in Kandal Province by Phan *et al.* [272] had arsenic concentrations in excess of 50 μg per liter. More than 10% of the 40,000 wells surveyed by Vietnam's Department of Water Resources Management during 2002 to 2008, and considered by Erban *et al.* [273] in their study of arsenic in the multi-layered aquifer system in the Mekong Delta, had arsenic concentrations in excess of the World Health Organization's drinking water standard of 10 μg per liter.

Millions of residents in South and Southeast Asia also are at risk from consuming rice with elevated arsenic concentrations in the grain. Among food crops, rice is notably efficient at accumulating arsenic [274,275]. Su *et al.* [276] report that rice takes up arsenite at twice the rate of wheat or barley. By comparison, the uptake of arsenate was similar for rice and wheat, but one-third less for barley. The condition in which rice is produced contributes to the potential for arsenic uptake and accumulation. Much of the world's rice is produced in paddies that are flooded to a depth of several centimeters for a large portion of the growing season. In anaerobic conditions, metal-reducing microbes transform arsenic into a mobile form that becomes available for uptake by the rice plants [277–279]. In areas where farmers irrigate rice paddies with arsenic tainted groundwater, the uptake of arsenic is enhanced [275].

Arsenic concentrations in rice fields can increase, over time, due to long-term irrigation with arsenic tainted groundwater. Concentrations also can vary substantially across an irrigated region, due partly to the initial distribution of arsenic, the variation in aquifer characteristics, and also to the mixing and cycling of arsenic that occurs with pumping of groundwater and the delivery of irrigation water across canal systems and farm fields [253,280–282]. In some areas, arsenic concentrations are higher in shallow wells than in deeper wells, such that some authors suggest preserving deeper aquifers for use as drinking water supplies, rather than extracting deeper water for use in irrigation [253]. Stroud *et al.* [283] observed substantial temporal and spatial variation in arsenic concentrations in soil and water in a small sample of paddy fields at four sites in Bangladesh and West Bengal. The concentrations of arsenic in grain varied within rice fields, and the variance could not be explained by variation in arsenic concentrations in soil. The authors conclude that arsenic behavior in soil pore water and standing water in rice fields is dynamic and complex [283].

Arsenic also poses a risk to rice plant performance. High arsenic concentrations can contribute to the development of straighthead disease, which can cause sterility after heading, in otherwise healthy rice plants [284]. Panaullah *et al.* [285] observed a grain yield gradient on a rice field irrigated from a tubewell for 16 years in Bangladesh. During two crop seasons, grain yields declined from about 8000 kg per ha to 2500 kg per ha, as the concentration of total arsenic in the soil, across the field, increased from about 12 mg per kg to 70 mg per kg. The yield decline was associated with a decrease in the number of productive tillers. The authors note, also, that while arsenic concentrations in the rice grain were relatively high, ranging from 0.3 mg per kg to 0.6 mg per kg, concentrations in rice straw were much higher, ranging from about 2 mg per kg to 12 mg per kg [285].

High concentrations in rice straw raise additional concerns regarding arsenic exposure, as rice straw is the primary feed material for cattle and buffalo in Bangladesh, and manure is burned in kitchens to provide fuel for cooking [285]. Ghosh *et al.* [286] report high concentrations of arsenic in drinking water and rice straw, and in cow's urine, dung, and milk in areas of Bangladesh with high concentrations of arsenic in groundwater. Arsenic concentrations in rice straw were higher in the *Boro* (dry) season, than during *Aus* or *Aman*. Concentrations were higher also in straw irrigated with water from shallow wells, rather than deeper wells. The authors suggest that the arsenic concentrations in milk might be harmful in areas where residents are exposed also to other sources of arsenic, such as drinking water and food, and that household burning of cow dung might become an environmental issue in Bangladesh [286].

Duxbury and Panaullah [287] describe three alternatives for sustaining rice production in areas with high concentrations of arsenic in groundwater, while not increasing human exposure to arsenic in rice:

1. Where possible, irrigate with surface water, rather than groundwater,
2. Cultivate rice in aerobic conditions, rather than flooding rice fields for the entire season, and
3. Where available, produce cultivars that have lower rates of arsenic accumulation.

Irrigating with surface water will reduce arsenic loading to soils, over time, yet arsenic uptake likely will continue in the near term, if rice is produced in anaerobic conditions [288,289]. Switching from flooded paddies to aerobic production can substantially reduce arsenic uptake in the near term [290,291]. The option of producing cultivars with lower rates of arsenic uptake depends partly on the success of rice breeding programs in developing such cultivars, which also must match farm-level and market-driven criteria for successful production and sale. Mitigation measures might also include reducing the amount of straw and other organic matter incorporated into rice soils, in arsenic problem areas, as microbes utilizing the additional organic matter consume oxygen, thus leading to a decrease in redox potential, which furthers the process of arsenic dissolution from iron oxides [292].

5.2. Water Management

In areas with high concentrations of both arsenic and cadmium in agricultural soils, choosing a water management strategy requires consideration of both elements. In some soils, the anaerobic conditions that characterize paddy rice production can promote the uptake of arsenic, while minimizing the uptake of cadmium [293–295]. Switching from anaerobic to aerobic production can have the opposite effect of minimizing arsenic uptake, while making cadmium more available to plants. The direction and magnitude of the uptake responses of arsenic and cadmium likely will vary with rice cultivars [293,294].

Arsenic uptake in rice can be reduced by switching from a program of continuous flooding to one of alternate wetting and drying. Linquist *et al.* [296] compared arsenic uptake on experimental plots in the southern United States, in a two-year study involving rice-rice (RR) and rice-soybean (RS) rotations. The irrigation treatments included continuous flooding (flooded control) and three versions of alternative wetting and drying: AWD/40F, AWD/60, and AWD/40. The numbers following the AWD designation represent the proportion of saturated volume at which the fields were re-flooded, after drying. In the AWD/40F treatment, the fields were managed in the same manner as the AWD/40 treatment, until the plants reached the reproductive stage. From that time forward, flooding was maintained until the field was drained for harvest [296].

The highest arsenic levels were observed in the flooded control and the AWD/40F treatments. Arsenic concentrations were reduced, on average, by 56% on the AWD/60 and AWD/40 treatments, in comparison with the flooded control. Regarding crop rotations, arsenic concentrations in rice grain were 20% higher, on average, in the RR rotation, in comparison with the RS rotation [296]. Across years and rotations, the highest grain yields were obtained on the flooded control and the AWD/40F treatments. Yields on the AWD/60 plots were similar to the control at two sites, but lower than the control at one site in one year. Average yields were reduced by about 13% on the AWD/40 plots, which received the smallest volume of irrigation water. The authors note that the AWD/40 treatment would not be desirable, as the AWD/60 treatment achieved a similar reduction in arsenic concentration (and methane emissions), while providing a higher yield [296].

Spanu *et al.* [291] compared arsenic uptake by rice on a field that was continuously flooded with a field on which sprinklers were used to deliver the irrigation water, at the University of Sassari in Sardinia, Italy. The authors observed substantial reductions in arsenic uptake on the sprinkler irrigated field. Some of the arsenic concentrations in the field approached background levels of arsenic in the irrigation water, leading the authors to suggest that very little bioaccumulation of arsenic might occur in the aerobic conditions maintained by irrigating rice with sprinklers. The authors note also that arsenic uptake varied across the 37 cultivars they examined, both on the flooded and sprinkler irrigated fields.

Moreno-Jiménez *et al.* [297] also observed substantial reductions in arsenic uptake when irrigating rice with sprinklers, in comparison with continuous flooding. During a seven-year experiment conducted in Spain, concentrations of inorganic arsenic in rice grain were up to two times higher on flooded plots. Concentrations of organic arsenic also were higher on flooded plots, but the difference was not as substantial. Similar grain yields of about 3000 kg per ha were obtained on both the flooded and sprinkler irrigated plots. Cadmium uptake in rice was substantially higher when irrigating with sprinklers. Cadmium concentrations in rice grain reached 50 μg Cd per kg during the course of the seven-year experiment on the sprinkler irrigated plots [297].

These results suggest that sprinkler irrigation is effective in reducing arsenic uptake in rice. However, the full cost of purchasing, maintaining, and operating a sprinkler system likely is excessive for many smallholder farmers. A more affordable alternative for reducing arsenic uptake in many areas of South and Southeast Asia is to produce rice in raised beds, and delivering irrigation water in furrows. Talukder *et al.* [288] observed substantial reductions in arsenic uptake on rice fields panted in permanent raised beds and irrigated in the furrows (PRB), in comparison with continuously flooded, flat fields (CTF) during a two year experiment in the arsenic-affected area of Gaibandha, Bangladesh. Arsenic uptake in both the grain and straw was significantly higher in the CTF plots than in the PRB plots. Specifically, the arsenic concentrations in grain and straw were about three times and seven times higher, respectively, in the CTF plots than in the PRB plots. The authors also observed significant increases in grain and straw yields, in both the *Boro* (dry) and *Aman* (wet) seasons. About 30% less irrigation water was applied on the PRB plots, thus notably reducing the amount of arsenic added to soils. In sum, the combination of raised beds and furrow irrigation reduced arsenic input to soils and arsenic uptake, while also improving grain and straw yields [288]. Further research is needed to fully understand the opportunities and challenges inherent in switching from continuous flooding to raised bed planting of rice in Asia [298].

Further research is needed, also, regarding the potential long-term implications of producing rice on raised beds. Singh *et al.* [299] observed declining yields of transplanted and direct seeded rice on permanent raised beds in a rice-wheat cropping system in Punjab, India. Root knot nematodes became established in the transplanted raised beds, while rice plants on the direct seeded raised beds suffered from severe iron deficiency. Kukal *et al.* [300] compared the soil bulk density profiles of permanent raised beds, with those of freshly formed raised beds, in a farm field near Punjab Agricultural University. The authors also measured the root mass density of rice plants in 5 cm increments of soil depth. Root mass density was significantly higher in the upper 15 cm of soil on the fresh beds. Soil compaction was evident along the edges of the permanent beds, but not along the fresh beds. The authors suggest that the soil compaction on permanent beds might be caused by tractor tires passing through the furrows during the bed re-shaping operations that occur after harvest, each year [300].

Kreye *et al.* [301] observed significant yield damage due to root knot nematodes on plots of direct seeded and transplanted rice cultivated in aerobic conditions in Central Luzon, Philippines. Pre-treatment of soil with the biocide dazomet reduced root galling due to nematodes on both the direct seeded and transplanted plots. In addition, rice yields were higher on the dazomet treated plots. The authors suggest that soil pH also might have had a role in generating the observed results, yet further study is needed, regarding the role of soil pH in the context of nematode damage, and the mechanism by which soil pH changed during the course of their experiment [301]. In a companion paper, the authors suggest that the use of irrigation water from shallow tubewells might have increased the soil pH, thus inducing micronutrient deficiencies [302]. The authors suggest also that further research is needed, regarding the role of micronutrients, especially iron and manganese, in contributing to the sharp reductions in yield and in the yield failures observed on aerobic rice fields in the tropics [303].

5.3. Silicon in Soils

Arsenic uptake in rice can be reduced also by applying silicon fertilizer to increase the availability of silicon in rice paddy soils. Rice is an efficient accumulator of silicon, just as it is of arsenic [214]. Arsenite, the most prevalent form of arsenic in flooded rice paddies, is a silicic acid analogue, and is taken up by rice roots due to its similarity to silicic acid [205,206,214,304,305]. Several authors have shown that when excess silicon is available in the soil or in hydroponic culture, arsenic uptake and translocation to plant shoots and rice grain are reduced [207,210,214,306,307]. Organic forms of arsenic also are taken up by rice, via the silicic acid pathway [207,305].

Li *et al.* [207] examined the effectiveness of silicon fertilizer in reducing arsenic uptake, in a pot experiment using soil from an arable field on the Rothamsted farm in southeastern England. The authors applied 20 g of SiO_2 silica gel per kg of soil, to provide a sparingly soluble source of silicon that did not affect soil pH. The silicon treatment increased grain yield significantly, while reducing the concentrations of arsenic in the straw and husk by 78% and 50%, respectively. The concentration of arsenic in rice grain was reduced by 16%. Pati *et al.* [308] obtained higher grain and straw yields when applying diatomaceous earth (63.7% SiO_2) in a two-year field experiment during the *kharif* season in West Bengal. The average grain yield obtained with standard fertilizer practices (N,P,K, zinc sulfate, and farmyard manure) was 4687 kg per ha. The average yields obtained on the treatments that also included diatomaceous earth (DE) were 4863 kg per ha (DE at 150 kg per ha), 4907 kg per ha (DE at 300 kg per ha), and 5219 kg per ha (DE at 600 kg per ha). The authors did not assess arsenic uptake or the economic implications of applying the selected levels of diatomaceous earth [308].

The agronomic gains of applying silicon to rice soils have been known for some time. Researchers in Japan began studying the role of silicon in rice production in 1917. They determined that rice leaves infected with blast disease had less silicon content than healthy leaves [304]. In the 1950s, in an effort to boost national food production, the Ministry of Agriculture, Forestry and Fisheries of Japan began promoting the use of slag from the iron industry as a fertilizer for rice fields, following successful trials at experiment stations across the country. The slag contains substantial silicon, largely in the form of calcium silicate, and is free of toxic components [304]. Thus, farmers utilizing slag as a fertilizer gain the benefit of higher yields, while also reducing the likelihood of arsenic uptake in rice grain.

In areas with high concentrations of arsenic in soils and groundwater, silicon amendments also can reduce the negative impacts of arsenic on rice plant performance. Sanglard *et al.* [309] report that in addition to reducing the uptake of arsenic by rice plants, silicon nutrition can offset to some degree the impairment to photosynthesis caused by arsenic accumulation. Sanglard *et al.* [310] also showed that silicon can reverse the carbon fixation impairments of arsenic in rice, which occur at the stomatal and mesophyll levels. Thus, silicon amendments to soil can provide multiple benefits in some settings, by reducing arsenic uptake, enhancing rice plant performance, and providing other biotic and abiotic benefits, such as enhanced resistance to the striped stem borer [311] and brown planthoppers [92].

Meharg and Meharg [214] propose two strategies for enhancing and sustaining silicon levels in soils: rice genetics and silicon fertilization. The authors describe initial efforts to improve understanding of the genetic variation in silicon content across rice cultivars, while calling for additional research to identify rice germplasm with high shoot silicon and demonstrating enhanced efficiency of assimilating silicon from soils. The most common forms of silicon fertilizers are industrial byproducts, including the slag from steel mills and blast furnaces [312]. Several naturally occurring minerals are available, such as wollastonite, olivine, and diatomaceous earth, but the cost of mining and transport can exceed the incremental value of use in agriculture [312]. A more affordable option might involve the composting of rice straw, for application to rice paddy fields [214]. However, the process is time consuming, requires space, and has fallen out of favor in countries, such as Japan, where the availability of farm labor has been declining, over time [304]. Research is needed to determine methods for accelerating the composting of rice straw, and for utilizing biochar derived from rice straw as soil amendments [214,313]. Incorporating the ash of rice straw and husks into paddy soils also can enhance silicon availability, thus improving rice plant performance, while not increasing methane emissions [204,314,315].

6. Conclusions

Climate change will impact rice production across a large portion of Asia. In some areas, crop yields will increase in some seasons, perhaps in response to higher rainfall at opportune times during the production cycle or with a reduction in cool, summer days in northern regions. In other areas, yields might be reduced due to higher night temperatures, untimely drought conditions, or submergence caused by large storm events. Improvements in water management will be helpful in adapting to climate change, particularly in areas where higher temperatures are likely and where shifts in rainfall patterns are expected. Switching from continuously flooded paddy rice production to intermittent irrigation will reduce irrigation demands in the dry season, when water might become more scarce with climate change. Many farmers also might need to modify their annual production programs to include just one crop of rice during the wet season, while switching to alternative crops in the second and third seasons. In any event, water management will be a key feature of production decisions aimed at adapting to the likely impacts of climate change.

Improvements in water management also will be helpful in reducing methane emissions and arsenic uptake in rice fields. Paddy rice production generates substantial amounts of methane annually, thus adding notably to the amount of greenhouse gases released into the atmosphere each year. Switching from flooded paddy production to aerobic rice production or to alternative crops that are produced in aerobic conditions can substantially reduce regional methane emissions. Nitrous oxide emissions can increase when switching from anaerobic to aerobic production, yet the change in production methods generally will reduce global warming potential.

Adopting some form of aerobic rice production also will reduce the release of arsenic from soils to groundwater, and the subsequent uptake of arsenic by rice plants. Arsenic accumulation in rice grain declines sharply when farmers switch from anaerobic to aerobic production methods. Millions of residents of South and Southeast Asia already are exposed to harmful concentrations of arsenic in drinking water. In those areas, and elsewhere, successful efforts to reduce arsenic uptake in rice will be helpful in reducing total exposure, to the benefit of many adults and children who currently consume harmful amounts of arsenic each day.

In paddy rice production areas with monsoonal climates, farmers likely will continue producing at least one crop of rice per year, given that rice production is well-suited to the monsoonal rainfall pattern. The crop calendar for rice might shift, in response to climate change, with implications for crop choices in the second and third seasons. Those choices will be influenced also by the availability of irrigation water in the dry season, expectations regarding the length of the wet and dry seasons, and the farm-level economics of crop production alternatives. Farmers also must consider the risks inherent in their crop production choices, and how those risks will be modified by climate change.

Farmers in many areas of Asia already are implementing adaptation strategies that have been formed, in part, by their long experience with shifting weather patterns and through efforts to increase rice yields. Regional and national investments in irrigation and drainage infrastructure, in plant breeding, and in efforts to transfer knowledge from research settings to the field will be helpful in achieving greater success with farm-level adaptation efforts. Farmers will benefit also from programs that provide timely projections of changes in weather and in the onset and termination of monsoon seasons. Rice production likely will remain the dominant agricultural activity and the primary source of livelihood for millions of smallholders in Asia for many years. Successful adaptation to climate change, in conjunction with substantial reductions in methane generation and arsenic uptake in rice fields will enhance livelihoods and improve public health across much of Asia.

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