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WETTING AND DRYING: REDUCING GREENHOUSE GAS EMISSIONS AND SAVING WATER FROM RICE PRODUCTION

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SUMMARY

A sustainable food future will require reductions in greenhouse gas emissions from agriculture even as the world produces substantially more food. The production of rice, the staple crop for the majority of the world's population, emits large quantities of methane, a potent greenhouse gas. According to various governments, global rice production emits 500 million tons of greenhouse gases (carbon dioxide equivalent) per year—or at least 10 percent of total agricultural emissions. The figure may be closer to 800 million tons when adjusted for new estimates by the Intergovernmental Panel on Climate Change of the sustained warming effect of methane. Although uncertain, there is evidence that increasing levels of carbon dioxide in the atmosphere could also increase future rice-related emissions substantially through its effect on soil microbes.

Most of the world's rice grows in inundated conditions, and one of the most promising techniques for reducing rice-related emissions is to reduce or interrupt the periods of flooding. The production of rice in flooded paddies produces methane because the water blocks oxygen from penetrating the soil, creating conditions conducive for methane-producing bacteria. Shorter flooding intervals and more frequent interruptions of flooding lower bacterial methane production and thus methane emissions.

Note: authors are listed in alphabetical order.

CONTENTS

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Techniques for reduced or interrupted flooding include (a) a single drawdown of water during the mid-season; and (b) alternate wetting and drying (AWD), which repeatedly interrupts irrigation, so that water levels modestly decline below the soil level before reflooding. Other techniques include dry seeding instead of transplanting rice into flooded fields, and various “aerobic rice” systems, in which rice is grown in well-drained soil. Evidence indicates that all of these techniques substantially reduce greenhouse gas emissions. Perfect water management can theoretically reduce emissions by up to 90 percent compared to full flooding. Numerous field experiments also suggest that if properly employed, these practices will at least maintain rice yields, and sometimes increase them. Many of the world’s rice-producing regions also face water shortages, underscoring the need for higher water use efficiencies at the field level for stabilizing yields.

But despite the potential benefits, our case studies from China, India, the Philippines, and the United States indicate mixed practical potential to adopt these water management techniques without improvements to irrigation or drainage systems. Farmers need reliable control over irrigation water to implement these measures, and generally also need small, well-leveled fields to assure that water levels do not drop too far in parts of the field, which would impact rice yields. Where farmers irrigate by pumping groundwater in India, the southern United States, and some parts of the Philippines, they generally have the technical ability to apply water saving techniques, at least during periods without substantial rainfall.

In the Philippines and many other Asian countries, farmers have limited technical ability to drain their fields during the rainy season, so full-scale AWD is probably not feasible. During the dry season, farmers who rely on surface irrigation systems tend to be reluctant to interrupt irrigation when water is available because of doubts that water will be available later when needed to refill the field. In some of these locations, dry seeding may be an effective means of reducing methane emissions, and in others, a single drawdown may still be feasible, but the technical opportunities remain generally unexplored.

Our case studies also reveal unexplained discrepancies in the observed impacts of water management techniques in different environments. Although farmers in China and Japan widely practice a single mid-season drainage because of a common understanding that it improves their yields, researchers have found no similar yield gains in the United States. There are many studies finding yield gains from AWD, but there are also studies showing losses. No one today can explain these differences fully. The scope of potential water savings associated with these water management techniques is also uncertain. AWD has been shown to reduce water use at the farm level, but the assessment of the actual water balance at the level of an entire irrigation system is more complex and remains an open question.

Overall, apart from our relatively broad analysis in these case studies, little information exists about precisely where, and under what conditions, these measures really present a benefit to farmers. Similarly, there is a lack of information about the relative cost-effectiveness of implementing these water management techniques in major rice-growing areas. Put simply, there are individual farm studies of the impacts and benefits of water management, and broad global analyses that require many assumptions, but the knowledge in between is mostly lacking. These challenges remain serious barriers to the wide-scale adoption of improved water management practices.

Rice farmers currently have only limited incentives to improve water management. In regions where farmers irrigate by pumping groundwater, improved water use efficiency can directly translate into reductions in fuel used for pumping water, and therefore lower production costs, if pumping is unsubsidized. In general, these are the prime areas with immediate opportunities to implement improved water management, and reducing water or pumping subsidies could help encourage these changes. Broader incentives will be necessary to encourage farmers in other areas to implement these practices at the necessary scale.

To fully realize the opportunities for water management benefits, we recommend that research organizations and government aid agencies fund coordinated assessments of the practical potential to implement different water management techniques at the irrigation district level. These organizations should also fund an improved global assessment of yield, greenhouse gas and water saving effects of these techniques based on a series of pilot projects. We also recommend that governments reform water and energy subsidies, and develop new affirmative incentives for water management, especially in water-stressed areas. Taken together, these measures have the potential to substantially reduce the environmental impacts of the world’s most important staple crop—and could constitute a significant step toward a sustainable food future.

THE AGRICULTURAL GREENHOUSE GAS CHALLENGE

The World Resources Report's *Creating a Sustainable Food Future: Interim Findings* (Box 1) analyzes a menu of solutions to the problems of how to meet global food needs in 2050 in ways that contribute to economic and social development and reduce agricultural impacts on the environment. Reducing agricultural greenhouse gas (GHG) emissions is among those core environmental needs.

Today, agricultural GHG emissions and associated land-use change probably generate around one-quarter of annual global GHG emissions.[1] To produce 70 percent more calories—needed to close a projected food gap by 2050—those emissions are likely to grow to a level that equals 70 percent of the total allowable budget of emissions from all human sources if the world is to hold global warming to acceptable levels. Such emissions from agriculture alone would almost certainly make it impossible to hold total emissions within the acceptable global limit because they would leave too little room for the much larger and still growing emissions from energy use in non-agricultural sectors such as industry and transport. If agriculture were to reduce its emissions in the same proportion as other sources to meet the generally recognized target of limiting global warming to just 2 degrees Celsius, agricultural emissions would have to decline by two-thirds from present levels even as agriculture produces 70 percent more food.

Previous installments in this series of working papers have focused on strategies to increase food production or decrease food demand in socially and environmentally beneficial ways. However, our *Interim Findings* make it clear that reducing agricultural GHG emissions to acceptable levels will also require changes in agricultural production practices motivated largely by their climate benefits.

Most of the world's rice grows in inundated conditions, which leads both to high methane emissions and to large demands for irrigation water. Many studies have shown that changes in water management could reduce GHG emissions from rice substantially. As a result, rice management has featured prominently in discussions about agricultural GHG emissions mitigation.

Box 1 | The World Resources Report: *Creating a Sustainable Food Future*

How can the world adequately feed more than nine billion people by 2050 in a manner that advances economic development and reduces pressure on the environment? This is one of the paramount questions the world faces over the next four decades.

Answering it requires a "great balancing act" of three needs. First, the world needs to close the gap between the food available today and that needed by 2050. Second, the world needs agriculture to contribute to inclusive economic and social development. Third, the world needs to reduce agriculture's impact on the environment.

The forthcoming World Resources Report, *Creating a Sustainable Food Future*, seeks to answer this question by proposing a menu of solutions that can achieve the great balancing act. This working paper profiles one of these solutions or menu items, and is one of a series of papers leading up to the World Resources Report.

Since the 1980s, the World Resources Report has provided decision makers from government, business, and civil society with analyses and insights on major issues at the nexus of development and the environment. For more information about the World Resources Report and to access previous installments and editions, visit www.worldresourcesreport.org.

This paper focuses on the existing evidence related to the opportunities and challenges of mitigating emissions through water management—both because of the significance of rice emissions themselves, and because it illuminates practical issues that will cut across the climate mitigation challenge more broadly. We address the various costs and benefits of the different water management approaches, including potential effects on yields. Because rice production has led to water shortages in many regions, we pay particular attention to potential water savings.

Improving water management in rice production satisfies the environmental criteria set forth in *Creating a Sustainable Food Future*—and can also satisfy the development criteria under certain conditions (Table 1).

Table 1 | **How "Improving Water Management in Rice Production" Performs Against the *Sustainable Food Future* Criteria**

● = positive ○ = neutral/it depends ⊗ = negative

CRITERIA	DEFINITION	PERFORMANCE	COMMENT
Poverty Alleviation	Reduces poverty and advances rural development, while still being cost effective	○	In some cases, improving water management in rice production can financially benefit farmers by lowering water costs, lowering electricity (pumping) costs, raising crop yields, and/or reducing labor costs. However, in many other cases, additional incentives will be necessary in order to make improved water management practices cost effective for farmers.
Gender	Generates benefits for women	○	On average, women provide nearly half of the labor input in Asia's rice-producing areas,[a] so they may stand to benefit from improvements in water management. However, the degree to which women benefit will depend both on their incentives to implement these practices, and their access to and control of resources related to rice production.
Eco-systems	Avoids agricultural expansion into remaining natural terrestrial ecosystems and relieves pressure on aquatic ecosystems	○	In some contexts, improving water management can increase rice yields and reduce pressure to convert additional land to agriculture.
Climate	Helps reduce greenhouse gas emissions from agriculture to levels consistent with stabilizing the climate	●	Interrupting flooding in rice paddies reduces the emissions of methane—a potent greenhouse gas—by reducing the populations of methane-producing bacteria and stimulating the breakdown of methane by other bacteria.
Water	Does not deplete or pollute aquifers or surface waters	●	Improving water management in rice production generally reduces demand for irrigation water, which can increase freshwater supply for other users or provide downstream ecosystem services. However, further analysis will be necessary to determine the extent to which field-level water savings translate into savings for an overall irrigation district or aquifer.

Note:
a. Mohanty and Bhandari (2014).

RICE AND GREENHOUSE GAS EMISSIONS

Rice is the staple crop for the majority of the world's population,[2] and rice production is a major source of employment and income, especially in developing countries. In 2013, farmers harvested rice on 165 million hectares worldwide, and flooded ("paddy") rice achieved a global average yield of 4.5 tons per hectare.[3] Although more than 100 countries grow rice, 90 percent of global production occurs in Asia. Of this production, irrigated lowland rice occurs on about 80 million hectares and produces 75 percent of the world's rice. Roughly 20 million of those hectares in Asia produce two or three crops of rice per year.[4]

Estimates of greenhouse gas emissions from rice production vary, but they all agree that rice production is a significant contributor to overall emissions. Rice produces roughly four times the GHG emissions per ton of crop as wheat or maize,[5] mostly in the form of methane and nitrous oxide. As in wetlands generally, flooding rice fields blocks oxygen penetration into the soil, which allows bacteria that produce methane to thrive. According to most estimates today, paddy rice methane generates roughly 500 million tons of emissions of carbon dioxide equivalent (CO_2e) per year. Using figures for the warming potency of methane established by the Intergovernmental Panel on Climate Change (IPCC) in 2006, we estimate that this number is actually closer to 600 million tons.[6] Further, new science suggests the number is even higher. A recent comprehensive assessment of the IPCC raised the estimate of methane's impact on global warming relative to carbon dioxide over 100 years by roughly one-third,[7] which implies that rice methane may be equivalent to around 800 million tons of carbon dioxide per year. Rice production also generates nitrous oxide, although IPCC methods suggest that emissions are small, at roughly 15 million tons of CO_2e. This figure is uncertain, however, and other estimation methods could raise it to 100 or more million tons.[8] Overall, therefore, paddy rice methane contributes at least 10 percent (and possibly more) of emissions from global agricultural production, and 1 percent or more of total human-generated GHG emissions. For most rice-growing countries in Southeast Asia, rice contributes around 50 percent of agricultural emissions and from 2.5 percent to more than 20 percent of total emissions.[9]

It is uncertain how much these emissions will grow between now and 2050 absent concerted mitigation efforts. The amount of methane emitted through rice cultivation depends far more on the area of land under production, and how that land is managed, than on the amount of rice actually produced.[10] Projections from the Food and Agriculture Organization of the United Nations (FAO) imply an increase in demand for rice of 30–40 percent by 2050,[11] which means rice yields need to grow at roughly 55 percent of their historical rate to keep within the net existing land footprint.[12] If paddy rice yields can grow fast enough to avoid expansion in rice area, methane emissions should not significantly grow according to present estimation methods. In fact, FAO projects that the harvested area of rice in 2050 will remain roughly the same as in 2006. Although yield levels have stagnated in roughly a third of rice-growing areas in recent years,[13] global rice yields have continued to grow and there appears to be sufficient growth potential to meet 2050 demands.[14] Limited land area suitable for growing rice, particularly in Asia, will also push farmers to try to increase yields rather than to expand land.

Unfortunately, climate change threatens both to decrease rice yields and to increase its GHG emissions. Some estimates of directly higher temperature effects on rice yields are harsh, on the order of 8–10 percent declines in yield for every 1 degree Celsius increase in temperature.[15] Millions of hectares of high quality, low-lying rice lands in Asia could be affected by sea level rise, increasing the risks of salinity and flooding. In addition, higher concentrations of carbon dioxide in the atmosphere appear to directly increase methane emissions by increasing the supply of carbon to the microorganisms that produce methane.[16] Although the science is evolving, one study estimated that the combination of lower yields and rising methane could double the emissions of each ton of rice by 2100.[17] This threat of growing emissions creates a strong need to reduce rice emissions in ways that boost—or at least do not harm—yields and therefore hold down rice land area.

PRIMARY RICE GREENHOUSE GAS MITIGATION STRATEGIES

Three principal strategies exist for mitigating GHG emissions from rice. The first is to increase rice yields. Increasing yields avoids increases in emissions from land-use change and from rice area expansion. If they are high enough, yield increases could even lead to reductions in rice area, reducing methane emissions as well as emissions from land-use change.

Second, better management of rice straw, the non-grain portion of rice plants, can hold down emissions. Methane emissions increase when fresh (non-composted) rice straw is added to flooded fields, particularly if not plowed in until just before planting. Yet rice straw burning, which occurs in some regions, also creates methane and other greenhouse gases, as well as local air pollution. Strategies that reduce emissions include incorporating rice straw into fields well before new production seasons, and removing rice straw from fields to use for other productive purposes, such as growing mushrooms, energy, or biochar.[18]

In this paper, we focus on the third strategy for mitigating GHG emissions from rice: reducing or interrupting periods of flooding. We focus on this strategy for its water savings potential and because among the three strategies, it could reduce emissions most dramatically. In addition, the challenges of improving water management illustrate the challenges of reducing agricultural GHG emissions more broadly.

WATER MANAGEMENT OPTIONS AND GREENHOUSE GAS REDUCTIONS

The longer rice is flooded, the more methane-producing bacteria grow and the more they generate methane. Decreasing the duration of flooding therefore reduces methane production and emissions.[19] The drawdown of water is accomplished by temporarily halting irrigation, allowing water levels to subside through evapotranspiration, percolation, and seepage. Interrupting flooding even with occasional drawdowns has a dual effect: it quickly drives down the populations of methane-producing bacteria, and it stimulates the breakdown of methane by other bacteria. Although the drop in methane emissions is not necessarily proportional to the duration of the drawdown, studies have found that almost any means of reducing or interrupting this flooding reduces methane emissions.[20] Even reducing flooding during the off-season—as many Chinese farmers do—can reduce emissions.

Systems for reducing flooding and emissions during the crop-growing season fall into four categories:

- **DRY SEEDING.** Most paddy rice production in Asia follows the traditional pattern of transplanting seedlings grown in nursery areas into already flooded paddies. But direct seeding of rice is growing in Asia and probably now accounts for a quarter of all rice production there.[21] Farmers in the United States use direct seeding because it requires less labor.[22] Direct seeding can occur in flooded fields or through drilling seeds into dry fields. If it occurs in flooded fields (wet seeding), it is unlikely to reduce methane emissions,[23] but if it occurs in dry fields (dry seeding), it reduces emissions because it shortens the flooding period by roughly a month.[24]

- **SINGLE MID-SEASON DRAWDOWN.** Studies have shown that a single drawdown during the crop production season, sufficient to allow oxygen to penetrate the soils, substantially lowers GHG emissions. Typically, this kind of drawdown must occur for 5–10 days to generate methane benefits.[25] Most farmers in China, Japan, and South Korea already practice this drawdown to increase yields.

- **ALTERNATE WETTING AND DRYING (AWD).** This practice involves repeatedly flooding a farm field, typically to a water depth of around 5 centimeters, allowing the field to dry until the upper soil layer starts to dry out (typically when the water level drops to around 15 centimeters below the soil surface), and then reflooding the field. This cycle can continue from 20 days after sowing until 2 weeks before flowering.[26] This approach is also known as "controlled irrigation" or "multiple irrigation," depending on country and research context. Because each drying cycle sets back the generation of methane-producing bacteria, AWD achieves even larger reductions in methane than only one drawdown. AWD can be practiced along a continuum, with the frequency of drawdowns ranging from more to less frequent, although the level of methane reductions will depend on how stringently it is practiced.

- **AEROBIC RICE PRODUCTION.** Like AWD, this system involves adding irrigation water only when needed. It avoids standing water, aiming instead to keep soils moist. This system can drastically reduce—or nearly eliminate—methane production. In general, however, aerobic rice production has lower yields than rice produced through traditional methods or the three methods listed above. Still, as our case study from China shows, some farmers are maintaining high yields by constructing raised beds and ditches, which limit standing water to furrows.

All of these systems will reduce methane emissions. Various studies have found reductions in GHG emissions from direct seeding in dry fields of 30 percent or more.[27] IPCC guidance provides that a single drawdown will reduce whatever emissions would otherwise occur by 40 percent, and multiple drawdowns by 48 percent.[28] However, these figures are averages. Evidence from the United States (described below) indicates that AWD could reduce emissions by as much as 90 percent.[29] There is also evidence that combining different water-saving approaches can have additive benefits for mitigation. For example, studies combining dry seeding with AWD have found emissions reductions of 90 percent.[30]

One concern is that while drawdowns decrease methane emissions, they tend to increase emissions of nitrous oxide, another powerful greenhouse gas. Nitrous oxide emissions are generally low in continuously flooded rice systems. However, under water-saving strategies, nitrous oxide emissions tend to increase because alternating patterns of oxygen in soils with new periods without oxygen maximizes the opportunities for nitrous oxide production. Data on nitrous oxide emissions under different water management regimes are limited to a few field studies with varying results. However, the findings indicate that the increased greenhouse gas effect from nitrous oxide is less than the reduction from methane—as long as excessive nitrogen is not introduced through high doses of fertilizer.[31] Reflecting this difference in impact, the IPCC guidelines do not account for increases in nitrous oxide emissions under water-saving techniques, and below we have chosen to follow this convention in our consideration of these techniques' GHG mitigation potential.

How much improved water management could mitigate emissions depends first on the extent to which these practices are already occurring. Unfortunately, good data on current water management practices are lacking. One commonly quoted global estimate of roughly 500 million tons of CO_2e associated with rice production is based in part on an assumption that most farms globally already practice some mid-season drainage, but that assumption now seems excessive.[32] High levels of mid-season drainage have been shown in China,[33] and farmers in Japan and Korea probably farm similarly. Together, these three countries account for 20 percent of global rice paddy area.[34] However, the view among agricultural researchers is that few farmers perform mid-season drainage in most other countries, which account for the remaining 80 percent of global rice paddy area. Adjusting the model in Yan et al. (2009) to reflect our rough estimate of 10 percent mid-season drainage rates in other countries raises our estimate of global methane emissions to roughly 600 million tons of CO_2e (using the 2006 IPCC figures for methane potency). As discussed above, this figure rises to roughly 800 million tons of CO_2e using the IPCC's most recent estimate of methane's global warming potential.

This estimate also implies that a majority of the world's rice fields do not employ some kind of mid-season drawdown and therefore could at least in theory reduce their emissions substantially. Even in areas practicing some mid-season drawdown, however, our case studies suggest a potential to reduce emissions substantially if farmers could fully implement AWD or possibly one of the aerobic rice opportunities under exploration in China.

POTENTIAL EFFECTS ON YIELDS

As our case studies show, evidence on the effect of these water management practices on rice yields is mixed. Data from some countries show that one drawdown or AWD increases yields, while other studies show that these practices have no effect on yields if done properly. In still other studies, there is some evidence that these practices decrease yields, particularly if not done properly.

In China, for example, an estimated 80 percent of farmers draw down field water levels for 7–10 days, because they have found that doing so increases crop yields; the drawdown suppresses the late generation of rice tillers (new small stems), which consume the plant's energy while producing few or no rice grains. Rice farmers in Japan also practice at least one drawdown. The high number of farmers in China who draw down their fields suggests yield benefits.

Many early studies found yield declines from AWD.[35] But as AWD became more widely practiced, studies in Asia typically found yield gains, including in the Philippines,[36] Vietnam,[37] and Bangladesh.[38] And studies in India have often found yield gains from AWD when practiced as part of a broader rice production system known as the "System of Rice Intensification" (Box 2).[39] Determining the precise reason for these yield gains requires further investigation, but there are at least three possible explanations:[40]

- Better resistance to lodging (bending over) of stems, attributable to better anchoring of well-developed roots or more sturdy stems
- More profuse early tillering (additional shoots), while mid-season drawdowns suppress unproductive late tillering
- In some cases, less susceptibility to disease (although other studies have found greater susceptibility to disease and weeds).

Box 2 | The System of Rice Intensification

The System of Rice Intensification (SRI) was originally developed in Madagascar as an approach to boosting the productivity of rice. It uses a water management practice similar to AWD that keeps soils moist but not saturated.[a] Additionally, SRI involves using organic fertilizers, spacing plants farther apart, transplanting younger plants, heavy weeding between rice plants, and plowing the soil between plants to increase oxygen penetration.

SRI is applied in many variations and does not always include the forms of water management profiled in this paper.[b] As such, even though studies have often found yield gains under SRI, such studies can only suggest—but not prove—yield benefits from the changes in water management alone.

Overall, the research community is divided about the benefits of SRI, although much of that debate centers on specific SRI practices and whether their benefits are worth the costs, particularly for commercial operations.

Notes:
a. Uphoff et al. (2011).
b. Ly et al. (2012).

Most recent studies in the United States (summarized in our case study below) have found that AWD had no effect on yields as long as soils retained an acceptable level of moisture at all times. Some studies, however, found small yield losses. Studies also indicated that yields could drop dramatically if soil was allowed to dry too much at any one time. U.S. yields are nearly universally high, indicating a persistently high quality of management, which may help to explain why changes in water management have not boosted U.S. yields.

Aerobic rice yields are generally 20–30 percent lower than flooded rice in good conditions, but aerobic production can boost yields where flooding conditions are unreliable.[41] Our China case study describes a "ridge and furrow" aerobic system that researchers have found to increase yields. This system avoids flooding rice altogether and instead keeps the soils continually moist.

Overall, the evidence indicates that AWD or one mid-season drawdown can increase yields in many cases and at least not harm yields in others, but some studies report yield declines. It is puzzling that so many rice farmers in China and Japan implement at least a single drawdown believing it will stimulate yield gains, while neither farmers nor researchers have found such gains in the United States. At this time, the science is unable to explain the differences in results or to support definitive findings of yield effects.

POTENTIAL WATER SAVINGS

Because farmers do not directly benefit from reducing greenhouse gas emissions, emissions reductions alone do not motivate adoption of these water management techniques. In contrast, many farmers do directly benefit from saving water, providing a potential incentive to reduce flooding. Rice production uses around 40 percent of the world's irrigation water,[42] and almost one-third of these areas experience water shortages,[43] including all of the areas in our case studies. As these case studies show, direct seeding into dry fields reduces water consumption because it reduces the inundation period as compared to growing rice seedlings in flooded nursery seedbeds. There is also compelling evidence of water savings at the field level for AWD. These water savings provide a public policy case to implement these strategies.

Significantly, however, all current estimates of water savings are at the field level and refer to the water applied by farmers. Evidence suggests that most or perhaps nearly all of the water savings will result from reduced percolation,[44] which implies that some of the irrigation water saved by an individual field would have otherwise recharged groundwater or been used further downstream.[45] In short, water savings at the individual field level do not necessarily mean that people or the environment downstream will always benefit. However, drawing irrigation water levels below the surface should reduce losses from evaporation, and doing so on a large scale could reduce the total water consumption in an irrigation district. Further analysis in each irrigation district will be necessary to determine the extent to which field-level water savings translate into savings for the overall district or aquifer.

PRACTICAL CHALLENGES

Despite the water savings—and possibility of yield benefits—from reduced flooding in rice production, many farmers face important technical and practical constraints to implementing such improvements.

The most obvious and immediate challenge for any mid-season drainage is that farmers must be able to manage their water reliably. To practice AWD, farmers must first be able to allow their fields to dry, and then they must have a reliable source of water to rewet their fields as soon as needed. Most rice-growing regions have distinct wet and dry seasons. In the wet season, farmers may not be able to drain their fields adequately. In the dry season, our case studies indicate that only some irrigation systems can provide water reliably enough to encourage farmers to practice AWD. Our California case study illustrates this challenge—even in an area with a sophisticated irrigation system, the mechanism for delivering water is too slow to supply all farmers at the same time.

Despite these practical challenges in drainage and irrigation, there are many opportunities today to increase adoption of AWD. As discussed in our case studies, farmers in some parts of India irrigate by pumping groundwater, which allows them to control their irrigation. In the southern United States, many farmers have started to construct their own small reservoirs either to handle all of their irrigation needs or to supplement irrigation from other sources.

In addition, even where water level management systems are not capable of full-scale AWD, farmers might have enough control to practice dry seeding, or to perform at least one drawdown during the production season. But some water management control is still necessary. For example, with dry seeding, farmers still need to be able to keep soils moist from the period after seeds are grown to when the rice plant emerges. Overall, our case studies suggest both that improvements in water management capacity will be necessary to allow many of the world's farms to practice AWD, at least in some seasons, and at the same time that many of the world's farmers already have a greater capacity to practice AWD than is currently happening.

INCENTIVES

Farmers practicing these improved water management techniques typically do so for at least one of three reasons. First, as in China, experience may have demonstrated yield gains. Second, farmers may face high pumping costs for water, which they can reduce through improved water management. Third, in the case of dry seeding, the system saves labor (compared to transplanting) while maintaining yields. Where labor costs are high and farmers have sufficient access to herbicides to control weeds, dry seeding can make economic sense.

However, as our case studies show, farmers have no direct incentive to adopt these practices for the specific purpose of reducing greenhouse gas emissions. Similarly, only in some contexts do water supply issues motivate farmers to engage in these practices, even when water is limited. Many farmers receive water through gravity-driven irrigation; because they do not pay for the quantity of water they use, these farmers rarely benefit financially from reducing that use. In groundwater systems, the incentives are more pronounced as farmers can benefit from reduced pumping costs. Yet even under those circumstances the incentives may not always be great where, as in India, electricity costs for groundwater pumping are heavily subsidized. Overall, these observations suggest that additional incentives would be needed for farmers to implement additional water management techniques to significantly reduce GHG emissions from rice production on a global scale.

CASE STUDIES

To shed light on the challenges and opportunities for using water management to reduce greenhouse gas emissions, we developed case studies in India, the Philippines, the United States, and China. The case studies draw on published and unpublished data, and on the experience of the authors. In each, we examine experience with water management techniques, the potential of irrigation systems to support changes, evidence of impacts on yields and on GHG emissions, and the need and potential for water savings.

India

India contains about one-quarter of the world's rice harvested area and produces around one-fifth of the world's rice.[46] This case study focuses on two major rice-producing states: Tamil Nadu and Punjab.

Tamil Nadu

The state of Tamil Nadu occupies the southeast part of peninsular India and is the sixth-largest rice-producing state in India. Rice production occupies roughly one-third of the region's nearly 6 million hectares, and 57 percent of the total cropland area is irrigated. At an average of 0.8 hectares, farms are generally small. Ninety percent of farmers, who hold 56 percent of the cropland area, are smallholders. In irrigated areas, farmers generally practice traditional paddy rice production, transplanting rice seedlings into flooded fields, and keeping farms continuously flooded until harvest. Despite wide seasonal fluctuations in rainfall, and per capita water resources that are only half of India's as a whole, the region produces 6.6 percent of the country's rice.[47]

In general, surface water irrigation in Tamil Nadu is unreliable, making it difficult for farmers who rely on surface water to practice AWD. However, slightly more than half of all irrigated area employs wells and groundwater.[48] In these areas, AWD is a technically viable option. However, many farmers would need to level their fields to ensure even water distribution.

In part because of water shortages, state officials are advocating a variation of AWD as part of a broader rice production system known as the "System of Rice Intensification" (SRI, see Box 2). In 2012 the Tamil Nadu Department of Agriculture reported that farmers were practicing SRI on more than 42 percent of irrigated rice area.[49] Half of Tamil Nadu's rice farms use wells, where AWD is a viable option.

If all farmers claiming to practice SRI were practicing some form of AWD, this figure would suggest that AWD had already reached close to its technical potential. However, the report apparently counts *any* farmers practicing *any* elements of SRI. In a study of one district, although half of responding farmers claimed to adopt some elements of SRI, only 11 percent of all respondents reported adoption of a high number of SRI practices, and the rate of adoption of improved water management was the lowest of any practice.[50] Based on this experience, we estimate that the actual practice of AWD in Tamil Nadu is very low.

Two studies have measured impacts on greenhouse gas emissions from SRI practices that included not only AWD but also weeding methods designed to facilitate input of oxygen into the soils, which may also help to lower methane. In Rajkishore and Sunitha (2013), continuous monitoring of methane emissions in two locations measured declines in methane emissions of roughly 30 percent. The study showed savings of roughly this magnitude both in the drier and in the so-called kharif (monsoon) season. Another study found reduced GHG emissions of 25 percent from SRI compared to conventional management.[51] That study also found increased yields, meaning the emissions per kilogram of rice declined by more than half.

The practice of AWD would appear to have substantial potential collateral benefits. Tamil Nadu suffers from a large water shortage. It annually withdraws around 7 million hectare meters of water, but the annual supply from rainfall is only around 5 million hectare meters. The result is that groundwater levels are falling, and some wells are drying. Around 85 percent of the sustainable groundwater resource is developed and more than half of those local aquifers have been declared overexploited. Much of the groundwater is saline and of poor quality, leading to dependence on surface irrigation and intensive management of rainfed areas with harvesting and storage of rainwater.[52] An analysis of SRI in four locations in Tamil Nadu found water savings of 37 percent.[53]

In addition, several studies have found yield gains from adoption of SRI. An evaluation of 100 farmers in the Tamiraparani basin found large average yield gains of roughly 1.5 tons/hectare.[54] A World Bank study found yield gains ranging from 4 to 26 percent across all farm sizes.[55] In general, studies of SRI have found that it increases production compared to low intensity production techniques. However, as discussed in Box 2, these studies that evaluate benefits of SRI do not isolate the yield effects of water management changes, and so do not definitively prove yield benefits of improved water management.

Overall, evidence from Tamil Nadu supports a potential for large greenhouse gas emissions reductions and water savings from the AWD component of SRI for roughly the half of farms that rely on groundwater pumping. The evidence also suggests, but does not conclusively demonstrate, the likelihood of yield gains. However, the evidence also indicates that few farmers are employing these water management measures, perhaps because their experience with them is limited. Farmers may be wary of the risk that water management might lead to additional weeding requirements or in some cases, disease. Farmers may need to gain more experience with water management techniques to become confident of their benefits.

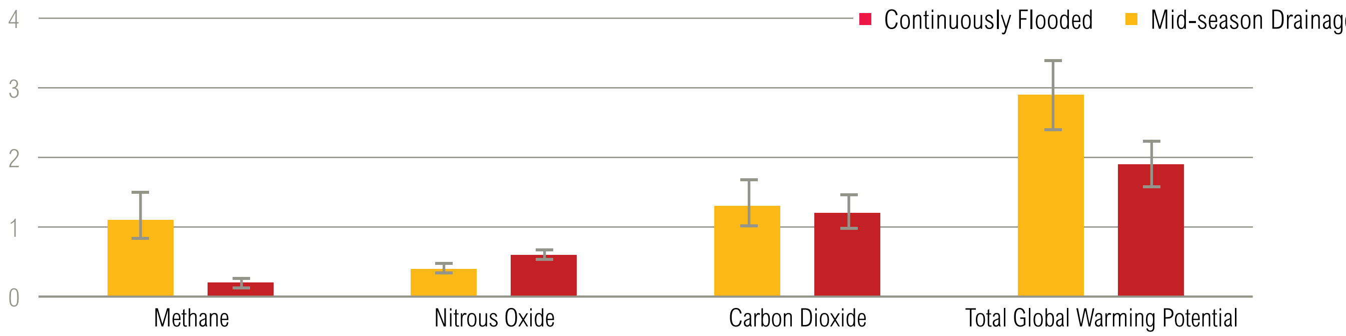
Government subsidies that lower the cost of water for farmers also may explain the limited adoption of water management measures in Tamil Nadu. State governments in India effectively provide free irrigation water,[56] and electricity for pumping water is highly subsidized and cheap. These subsidies reduce incentives for farmers to conserve water.

Punjab

Punjab, which cuts across the north of India and is characterized by wide variability in rainfall, topography, and soils, was not traditionally a large rice-growing region. In 1965, rice occupied only around 0.3 million hectares and produced one ton per hectare. But the Green Revolution turned Punjab into the rice bowl of India, with rice occupying nearly three million hectares by 2011–12 and producing 3.7 tons per hectare. Roughly one-third of all farmers have holdings smaller than two hectares, although almost two-thirds of actual farmland is held in farms from two to ten hectares.[57]

As in Tamil Nadu, canal-based irrigation systems are generally not reliable enough to support AWD in Punjab, but roughly three-quarters of the irrigated area is covered by tube wells, which can generally be tapped to provide water when necessary. In addition, porous soils mean that fields would become dry without irrigation even in the wet season, so drainage is not a problem. The logistics of irrigation are therefore mostly capable of supporting AWD in Punjab.[58]

Figure 1 | **Mid-season Drainage Reduces Greenhouse Gas Emissions from Rice Production in Punjab By One-Third (Tons of CO_2e per hectare)**



Source: Pathak et al. (2012).
Note: Solid bars show state-wide averages. Error bars represent one standard deviation.

Farmers and researchers in the region have experimented with a variety of alternative water management measures, largely driven by the desire to conserve water. Dry seeding of rice is an emerging production system in Punjab, although it still occupied only around 5,000 hectares in 2012.[59] Studies have found that it saves irrigation water by about 30 percent at the field level. One study found yields declined 1.0–3.4 percent for some varieties of rice, but increased 6.1 percent for others.[60] A recent survey of more than 300 randomly selected farmers showed that the yield decline under dry seeding resulted from non-adherence to a recommended fertilizer schedule and weed control package.[61] The Punjab government aimed to increase areas under dry seeding by 50 percent in 2013.[62]

There has also been some modest adoption of AWD as part of the broader adoption of SRI in Punjab. However, there has probably been even less uptake in Punjab than in Tamil Nadu, as SRI is less actively promoted or practiced in Punjab.

Studies have confirmed greenhouse gas emissions reductions both under AWD and under a single mid-season drainage. For mid-season drainage, the average emissions reductions have been by roughly one-third (Figure 1).[63] Direct-seeded rice—and direct-seeded rice with "brown manuring" with *Sesbania*[64]—reduced the global warming potential (GWP) of rice production by 70 percent and 43 percent respectively relative to transplanted rice.[65]

As in Tamil Nadu, improvements in water management could offer substantial collateral benefits in Punjab—where there is also an urgent need to reduce water use. Although annual renewable water resources are 3.5 million hectare meters, annual withdrawals are 4.8 million hectare meters.[66] Farmers meet the annual deficit by overexploiting groundwater, leading to declining groundwater tables. In central Punjab, groundwater declined by more than half a meter per year from 1993–2003, and in some areas of Punjab the water table is now being depleted at nearly 1 meter per year.[67] The area of Punjab with a water table depth of 10 meters or more increased from 20 percent in 1998 to nearly 60 percent by 2006.[68] This decline has imposed heavy costs:

- The cost of installing and operating tube wells has increased several-fold.
- About 30 percent of the total electricity in the state is now being used for pumping water for irrigation.
- Poorer water quality is contributing to increased salinity in soils.
- Some water now being pumped is contaminated by arsenic and fluoride, which is a major concern for human health.

As in Tamil Nadu, government subsidies reduce incentives for farmers to engage in water management practices that also reduce greenhouse gas emissions. Water withdrawals from tube wells are free. Electricity is also heavily subsidized. One study found that subsidies averaged US$110 per hectare in 2003–04, with medium and large farms receiving three-quarters of the subsidies.[69]

Because current trends in groundwater exploitation are unsustainable, the Punjab government has released a plan to reduce the area under paddy cultivation by around 1.2

million hectares, or more than 40 percent.[70] Improving water management on existing rice fields might substantially lower water use and therefore contribute to savings without such large cuts in rice production.

Overall, although there appears to be substantial potential for various forms of water management that would save water and GHG emissions in Punjab, there is limited experience and limited local demonstration of yield consequences. Incentive structures are not in place to encourage alternative water management.

Philippines

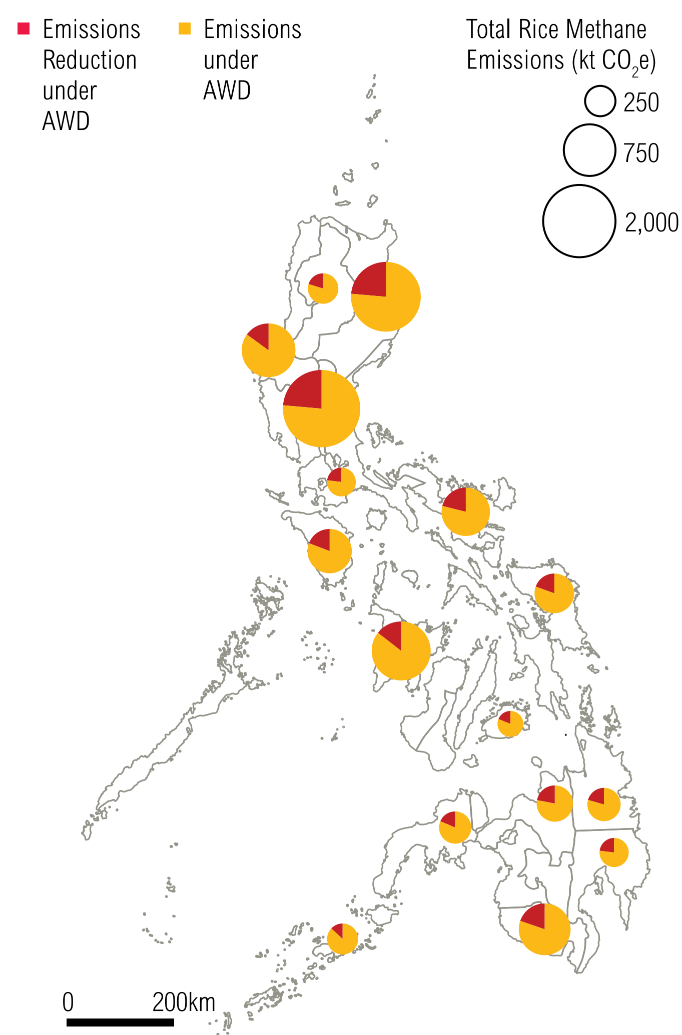
The Philippines ranks eighth in global annual rice production and is among the top rice-importing countries, with the largest annual rice imports globally from 2008 to 2010. The country's rice area has expanded from nearly 3.8 million hectares in 1995 to about 4.4 million hectares in 2010.[71] Nevertheless, the Philippines' rice area per capita is low compared to other Southeast Asian countries, contributing to its persistent need for rice imports. Other factors driving imports include high population growth and per capita consumption of rice coupled with production constraints (see below). Modern high-yielding varieties account for the vast majority of rice production, with less than 3 percent of production coming from traditional varieties. Average yield increased from 2.8 t/ha in 1995 to 3.6 t/ha in 2010, but it was still far below the potential yield for modern varieties.

Roughly 70 percent of the Philippines' total rice area is irrigated.[72] The remaining 30 percent is mainly composed of rainfed paddy rice and a small portion of upland rice; these non-irrigated areas are found in northern Luzon and the Central Visayas. The island of Luzon hosts almost 50 percent of the country's rice land, including the country's "rice bowl" in the central plain, which accounts for 19 percent of rice area. Rice production in irrigated areas occurs in distinct seasons, wet and dry.

Philippine rice production suffers from biophysical and socioeconomic production constraints. Population growth leads to declining agricultural land area, while input costs for more intensive cultivation are often too high for resource-poor farmers. Inadequate irrigation coupled with poor drainage limits water management options in wide parts of the country. Typhoons frequently damage rice infrastructure (levees and irrigation systems), and successive heavy rains during the monsoon season often cause flooding problems in paddy fields.

Heavy rainfalls during the wet season, which keep water levels high even without irrigation, limit farmers' ability to adopt AWD and other forms of water management. Although it is likely that many farms could conduct a single drawdown during the wet season, rainfall conditions would generally prevent full adoption of AWD. For this paper, the International Rice Research Institute (IRRI) calculated that if all irrigated farms throughout the Philippines implemented AWD in the dry season, they could reduce the country's total rice methane emissions by 20 percent, using IPCC emissions factors (Figure 2).[73]

Figure 2 | **Application of AWD in the Dry Season Could Reduce Rice Methane Emissions by 20 Percent in the Philippines**



Source: IRRI author calculations for this paper.
Image source: Map of Philippines, Single Color by FreeVectorMaps.com.
Notes: Emissions calculations under AWD assume AWD application in irrigated rice during dry season (January–June). Emissions data are from the year 2013. Emissions are shown by administrative region of the Philippines, aggregated from data per province.

Even in the dry season, however, the unreliable irrigation supply limits the present capacity of farmers to adopt AWD. Nationally, 86 percent of irrigation water comes from surface water irrigation and only 14 percent from groundwater.[74] Surface water can be subdivided into two sources: reservoirs and river diversion. The latter is the most abundant source in the Philippines as rivers supply about 75 percent of all irrigation water.[75] Surface water irrigation—and river-based systems in particular—are generally not reliable, and farmers at the tail end of the canals often suffer water shortages. Water scarcity becomes a prevailing problem during especially dry years, such as in El Niño events. Some irrigation schemes also are constrained by demands from non-agricultural users; the Angat-Maasim River Irrigation Scheme in Central Luzon, for example, supplies drinking water for Manila (see below).[76]

AWD has its greatest potential for uptake among farms with groundwater irrigation capacity. Privately owned pump irrigation from groundwater has been steadily increasing thanks to water shortages and the availability of cheaper pumps. By 2005, about a quarter of all rice farms used pumps to access groundwater.[77] A study of one irrigation system in Central Luzon showed that 10,000 farms (about 20 percent of the area under rice) had a pump density of at least one pump per 10 hectares.[78] Pumps are especially abundant at the tail end of secondary or tertiary canals.

To date, no published studies have recorded GHG emissions under AWD in the Philippines, but three studies have evaluated a single drawdown (Table 2). Methane emissions have generally been reduced by large amounts under single drawdown as compared to continuous flooding. The exception was one experiment that occurred during a period of heavy rainfall, which probably stopped the aeration of the soil and should therefore not be taken as a valid finding. Emission rates under a single drawdown were 17.9 to 92.5 percent of those under continuous flooding.[79]

Table 2 | **Compilation of Field Studies on GHG Emissions under Continuous Flooding and Single Drawdowns in the Philippines**

STUDY	LOCATION	METHANE	
		EMISSIONS UNDER CONTINUOUS FLOODING (KG/HA/SEASON [KG/HA/DAY])	RELATIVE EMISSIONS UNDER SINGLE DRAWDOWN (PERCENT)
Corton et al. (2000)	Maligaya, Nueva Ecija	89 [0.91]	57.1
		75 [0.73]	63.0
		348 [3.75]	92.5
		272 [3.23]	55.1
Wassmann et al. (2000)[a]	Los Baños, Laguna	251 [2.51]	17.9
		10 [0.10]	80.0
		35 [0.35]	31.4
Bronson et al. (1997)	Los Baños, Laguna	17.3 [0.20]	38.5
		371 [4.36]	57.2

Notes: a. This list excludes one field experiment from this study that was impaired by heavy rain, preventing drainage.
All studies used automated systems.

Farmers in the Philippines have been introduced to AWD in part through an initiative of IRRI and its national public research partner institutes (e.g., PhilRice). The initiative encourages farmers to practice "safe AWD," leaving sufficient saturation to avoid yield declines.[80] Farmers are advised to drain their fields one to two weeks after transplanting until the water level reaches around 10–15 centimeters below the soil surface. They then reflood the fields to a depth of around 5 cm before redraining. The number of days that the soil is not flooded can vary from one to more than ten, and farmers are taught to monitor the depth of the water table in the field using a perforated water tube. Farmers continue this routine throughout the cropping season except from one week before to one week after flowering. The threshold of water at 15 centimeters below the soil surface is considered "safe" because it allows the roots of the rice plant to capture sufficient water from the saturated soil to prevent yield declines.

In different parts of the Philippines, farmers have been encouraged to adopt AWD as part of a package of improved crop management practices aimed at farms that rely on pumping water. According to Mariano et al. (2012), 49 percent of all targeted rice farmers adopted AWD. The rate of AWD adoption was lower than the adoption rate of modern rice varieties (90 percent), but higher than the adoption of other innovations, such as "leaf color charts" to optimize fertilizer use.[81]

Efforts in central Luzon have targeted farmers who rely on pumping to adopt AWD. Central Luzon comprises seven provinces and has 300,000 hectares of rice, making it the largest rice producing area of the Philippines. The region has multiple irrigation systems that supply 92 percent of irrigation water, while groundwater supplies only 8 percent.[82] One study has evaluated impacts of AWD on rice yields in central Luzon, and found no statistically significant impact on yields under AWD. It also found no change in labor costs, which also suggested no increase in weeding problems.[83]

Studies have substantiated water savings from AWD at the field level. The central Luzon study found that farmers did respond to education about the opportunity for irrigation savings, and that farmers who adopted AWD reduced their hours of irrigation by 38 percent.[84] Other studies found water savings of 15–30 percent.[85] (As noted above, these savings do not all accrue to the irrigation system as a whole because some of the saved water would become available to other farmers.[86])

These studies have confirmed farmers' willingness to switch to AWD where the costs of pumping water are high, but not where costs are low.[87] In gravity-driven irrigation schemes, farmers typically pay a fixed irrigation fee per hectare, usually about US$50–$70 per season, and therefore have little financial incentive to use irrigation water judiciously. However, farmers relying on pumps to supplement surface deliveries at the downstream section of canals are more interested in water savings to reduce pumping costs.

Bohol Island

The most extensive adoption of AWD in the Philippines has occurred on the island of Bohol in the Visayas. In 2005 the National Irrigation Administration (NIA)—with the assistance of the Japanese government—constructed a new dam to address declining and unreliable water supply. This new dam generated a far more reliable source of irrigation water. To optimize use of irrigation water from the new dam, NIA imposed an AWD irrigation schedule in 2006. Each farmer has irrigation water for three days, then none for the next 10 to 12 days. The rotation of water is divided between upstream and downstream users. Downstream farmers receive water first so they can plant ahead by about one month. The reliable flow of water, even in a surface-water system, has allowed AWD to be successful.

Farmers have seen a range of production benefits. Farmers have been able to cultivate a larger area with a 16 percent increase in irrigated land, and in some parts of the island, they have been able to plant two rice crops each year instead of one. A study found yield increases of 11–13 percent, but noted that other improvements in crop management beyond AWD may have contributed to this improvement.[88] Along with other developments, AWD has helped Bohol reach rice self-sufficiency even as rice consumption per person increased.[89]

In most of the Philippines, unreliable supplies of surface water irrigation generally present a major impediment to AWD. Where they rely on pumps, farmers are often reluctant to try AWD because it is new. Experience has shown, however, that farmers are willing to adopt AWD when they are confident there will be no negative effect on rice yields and that enough water will be available when they need it. Broader adoption of AWD in the Philippines will require more reliable irrigation supplies, as on Bohol Island.

In the absence of more reliable irrigation supplies, a single drawdown may be more feasible both during the wet season and the dry season. However, a single drawdown is unlikely to provide large-scale water savings, and farmers will require other incentives to practice drawdowns on a meaningful scale. Pilot programs that encourage single drawdowns will be necessary to gain the experience to support more elaborate incentive programs.

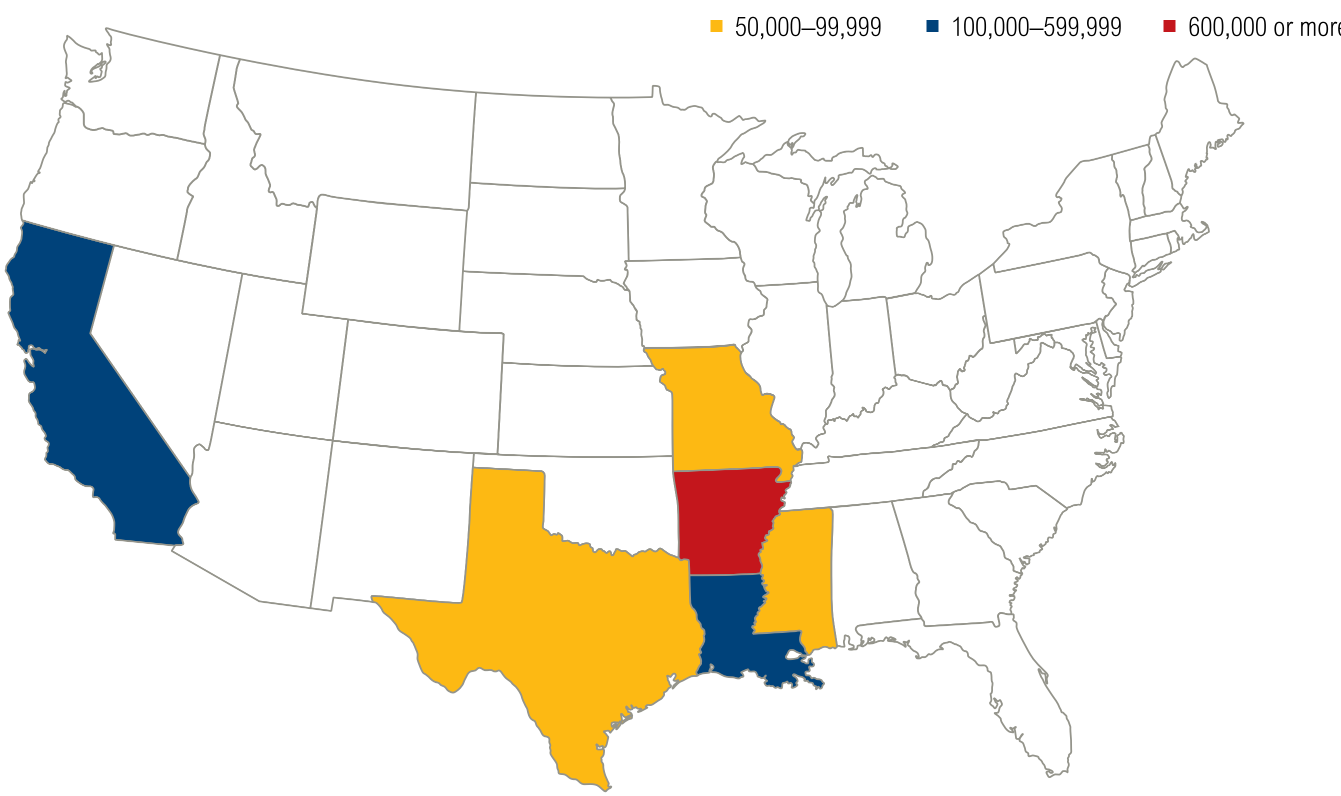
United States

The United States produces only 1.1 percent of the world's paddy rice and harvests only around 0.6 percent of the world's rice area.[90] Nevertheless, it has high yields of more than 8 tons per hectare and contributes 10 percent of the rice sold across countries.[91] Six states produce nearly all U.S. rice: Arkansas, California, Louisiana, Mississippi, Missouri, and Texas (Figure 3). Half of U.S. production comes from Arkansas, while California attains the highest yields. Unlike the small rice fields of Asia, single rice fields in the U.S. are typically between 20 and 50 hectares, with some much larger. U.S. rice production uses advanced equipment and inputs, and is 100 percent irrigated, so it provides a good illustration of the opportunities and challenges for mitigation of rice emissions with advanced production techniques.

Because rice fields in the United States are large, farmers usually divide them into separate basins, separated by levees, with weirs (dams) that control water heights and allow water to move from one basin to another in a controlled fashion. To improve water management, many farmers have carefully leveled their fields, sometimes preserving a gentle slope so water can pass from one field to another.

U.S. growers establish their rice through direct seeding rather than transplanting. In the southern United States (including Arkansas) most rice is dry seeded, which means the seed is planted and managed like other cereal crops for the first month, after which the field is flooded for the

Figure 3 | **Rice is Grown in Six U.S. States (Planted rice hectares, 2014)**



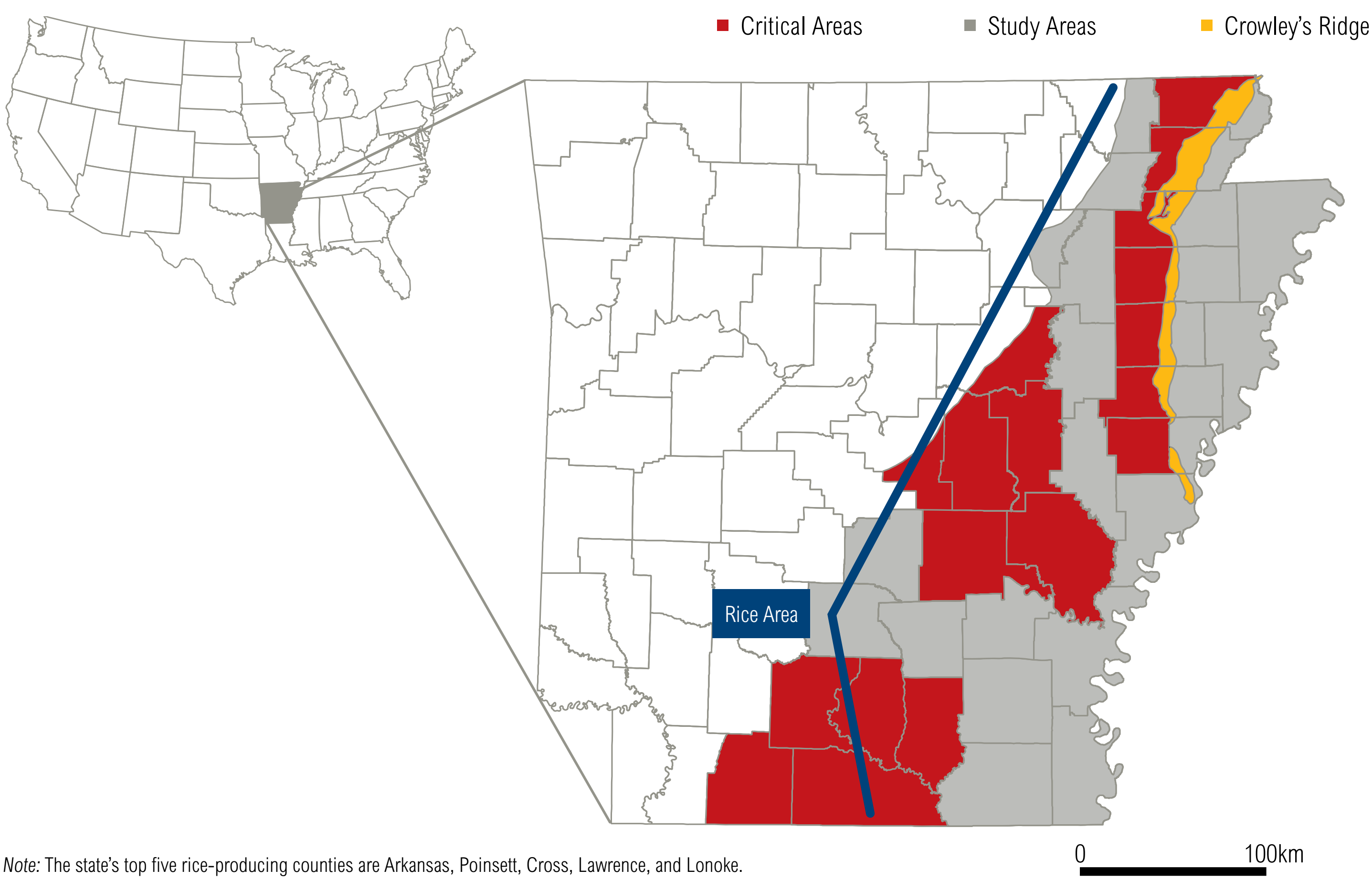
Source: USDA-NASS (2014).

remainder of the season. In California (and to some extent in Louisiana), rice is established by water seeding. In this system the fields are all flooded before planting and seed is flown aerially into the field. Because water-seeded systems typically remain flooded throughout the season, they are flooded overall for about one month longer than dry-seeded systems.

The technical capacity of rice farmers in the United States to adopt AWD or single drawdowns is not constrained by drainage. Growing season rainfall is sufficiently low that farmers can allow fields to dry as part of AWD.

The potential to adopt AWD in the United States therefore primarily depends on irrigation systems. The rice growing regions of Arkansas and Mississippi receive substantial rainfall of at least 480 mm/year during the growing season, but growers must also rely heavily on irrigation. Nearly all of that irrigation comes from wells. These regions sit over a shallow alluvial aquifer that rests above the deeper Sparta aquifer, and farmers typically pump from 20 meters and below. Due to overpumping, however, there are large regions within Arkansas where the aquifer can no longer provide sufficient water for rice production, while in other regions, farmers are going deeper and deeper, increasing their water costs (Figure 4). In response, in parts of Arkansas, farmers have built on-farm reservoirs, which they fill with rainfall runoff during the winter and use as their main water source during the growing season. This combination of reliance on well water, and the increasing number of on-farm reservoirs, ensures a high degree of control of irrigation water. The main impediment to AWD adoption is therefore the large size of fields, because farmers who rely on water to flow from one field to another are unlikely to have sufficient control over water levels to be able to use AWD with confidence. By constructing multiple systems to add irrigation water both to each field and in some cases within fields,

Figure 4 | **The Top Rice-Producing Counties in Arkansas Are Listed As "Critical" for Groundwater Availability**



Note: The state's top five rice-producing counties are Arkansas, Poinsett, Cross, Lawrence, and Lonoke.
Source: Arkansas Natural Resources Commission (2011).

farmers can manage water levels in large fields more uniformly and have the capacity to implement AWD.
In contrast, opportunities for AWD adoption are considerably lower in California. Because the region's Mediterranean climate generates little to no rainfall during the summer growing season, farmers rely on water deliveries from large, regionally managed water systems fed heavily by snowmelt and reliant on gravity. Farmers therefore do not have direct control over their water and their supply varies depending on other needs within their irrigation district. Widespread adoption of AWD is unlikely because California's irrigation systems are generally unable to supply water with sufficient speed to all farmers at the time it is needed.

Overall, few if any farms practice either AWD or a single-season drawdown in the United States. Research on AWD has occurred on relatively small plots, and farmers remain concerned about yield effects.

In both the southern United States and California, recent studies have confirmed large greenhouse gas reductions from AWD. In Arkansas, a recent study of AWD found reductions in total emissions of 45 to 90 percent.[92] And in California, a study found emissions reductions of 90 percent when AWD was combined with dry seeding.[93] A third study has found nearly 50 percent reductions in methane emissions from dry seeding, which floods fields about one month less than water-seeded fields.[94]

Studies of yield effects of AWD have shown sensitivity to the precise level of drawdown. A recent study in Arkansas found no yield declines as long as soils were kept at least 40 percent saturated, although more extensive drying caused yield declines.[95] Although some early informal AWD studies in California found yield declines, more formal studies just taking place now are finding no yield declines.[96]

In theory, AWD could prove attractive because of water savings. In Arkansas, aquifers are receding due to overpumping, and a recent study found increases in water use efficiency from AWD of 22 percent at the field level.[97] California faces even more severe water shortages. Drought is now leading to heavy restrictions on the delivery of irrigation water, but AWD is unlikely to reduce water use in California. Soils in California are heavy clay, so there is very little percolation loss when soils are flooded. By contrast, the heavy clay soils crack when drying, which would increase percolation losses through these cracks after reflooding.

As for other water management techniques, dry seeding is already the dominant seeding practice in the southern United States. Currently, however, only about 5 percent of farmers in California dry seed.

Overall, the potential for water savings and greater control over irrigation water make AWD a potentially attractive option in Arkansas. Yet because fields are large and have variable soil textures, farmers will be concerned that water levels may become too low in parts of their fields to maintain yields. To address these concerns and encourage broader adoption of AWD, large-scale demonstrations will be necessary. In California, a lack of potential water savings under AWD, and less control over irrigation make increased use of dry seeding the most presently promising strategy for reducing emissions through water management. Since dry seeding can increase the need for weed control, additional incentives will be necessary to persuade farmers to adopt the practice.

Various rice management practices are now listed on the American Carbon Registry (ACR) as greenhouse gas emissions mitigation strategies eligible for generating and selling credits to power plants and other companies that wish to reduce their net emissions.[98] This registry may provide farmers a new incentive to increase adoption of these practices. In both California and the southern United States, eligible ACR mitigation activities include removal of rice straw from the field after harvest, and early drainage at the end of the growing season. In California, replacing water seeding with dry seeding is also eligible, while intermittent flooding similar to AWD is eligible in the southern United States.

China

Farmers in China harvest almost 20 percent of the world's rice fields by area and produce almost 30 percent of the world's rice.[99] The vast majority of China's farmers broadly practice at least one mid-season drawdown. Although most rice is grown on well-irrigated flatlands, much is still grown in hill environments. This case study focuses on new techniques in Sichuan Province that hold promise for reducing greenhouse gas emissions while increasing yields and saving water.

Rice occupies roughly half of Sichuan Province's arable land. Of Sichuan's 3 million hectares of rice, 2 million hectares are in hill areas. This varied terrain makes rice fields harder to irrigate, and more vulnerable to droughts. The hilly terrain limits yields, increasing GHG emissions per ton of rice. Although farmers have long practiced intermittent flooding to reduce water consumption—with the side benefit of reducing methane—farmers also tend to keep fields flooded in the winter to ensure that water is available in the spring, when droughts are frequent. This maintenance of standing water in the winter increases GHG emissions.

The new techniques used in Sichuan Province rely on plastic covering as mulch. As shown in Figure 5, farmers construct a series of furrows and raised beds, cover the beds with long strips of thin plastic film 1.5 to 2 meters wide, punch holes in the film, and transplant rice into the holes. Furrows are roughly 15 centimeters deep. Farmers maintain water in the furrow for approximately 1.5 months after transplanting seedlings, but no water on the bed surface. Furrows are drained for around two weeks in the middle of the season to inhibit late-emerging unproductive tillers, to remove toxic substances, and to improve root activity. Farmers then restore water to the furrow until the rice is ready for harvest.

Figure 5 | **New Rice-Growing Techniques in Sichuan Province Use Furrows, Raised Beds, and Plastic Covering As Mulch**

Image source: Jing Ma.

Research has found that plastic film mulching reduces GHG emissions by maintaining higher oxygen content in the rice bed and thereby reduces methane-producing bacteria. According to two studies[100] in Sichuan Province, the decrease in methane emissions was 7.5 tons of CO_2e per hectare. The practice does increase nitrous oxide emissions by roughly 1.4 tons of CO_2e per hectare, so net savings of GHG emissions are 6.1 tons. The emissions involved in the production of the plastic film only add around 0.1 tons of CO_2e per hectare.[101] Counting all sources of emissions, these studies suggest GHG emissions reductions of roughly 50 percent per hectare, and 55–60 percent per ton of rice.

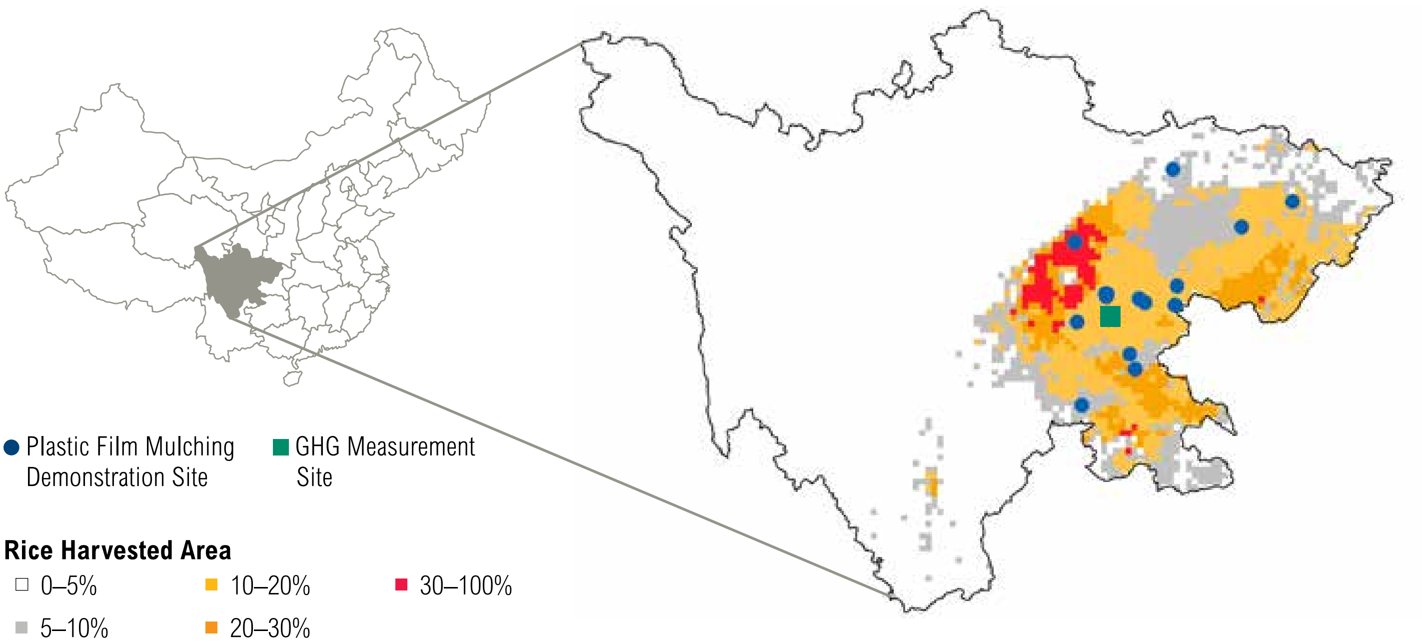
In addition, field experiments have shown that the emissions of nitrous oxide from the use of plastic film can be cut in half by the use of a nitrification inhibitor, which slows the microbial conversion processes that lead to the release of nitrous oxide.[102] Using nitrification inhibitors would therefore increase greenhouse gas emissions savings to roughly 60 percent overall.

Studies have also found yield and water benefits. In controlled comparison studies, plastic film mulching tends to raise yields by 5 to 20 percent.[103] This yield gain seems to occur largely because the plastic film traps heat and leads to increased soil temperatures in the spring, which stimulate greater plant growth in these cold terrains. These studies probably underestimate yield gains in practice because they assume that the alternatives to use of the film still achieve full irrigation, so the studies do not factor in the increased capacity to produce during droughts. Scientists have reported water savings per hectare of 58–84 percent and increased water use efficiency of 70–106 percent when factoring in the benefits of increased yields.[104] Furthermore, higher uptake of nutrients under plastic film mulching can lead to improved protein content and rice quality.[105]

There have also been economic studies of plastic film mulching technology, which have found overall economic savings. Decreased costs for fertilizer and pesticides themselves almost balance out the costs of the film, and savings in labor from reduced weeding and yield gains combine to imply large economic gains.[106]

In lowland parts of Sichuan Province, the use of plastic does not boost rice yields because soils are warm enough that they do not benefit from the increased warming, but a similar cultivation method has been developed without the film. Called either ridge-ditch cultivation or aerobic

Figure 6 | **Plastic Film Mulching Is Spreading through the Rice Area of Sichuan Province but Occupies a Modest Portion of Total Rice Production**

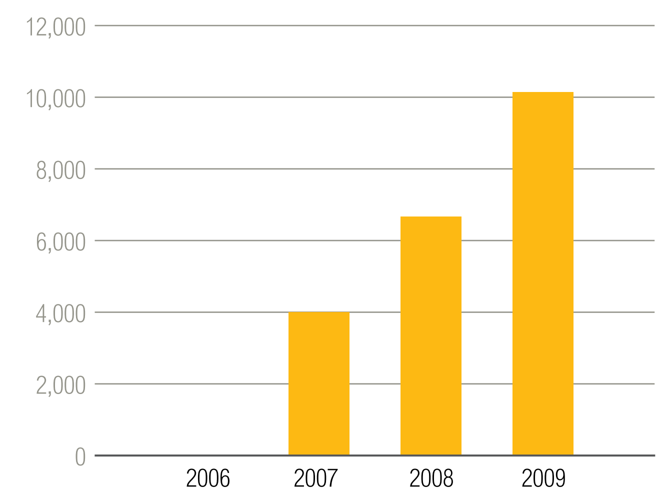


Source: Rice harvested area from Monfreda et al. (2008), demonstration sites from various media reports and publications.

cultivation,[107] it too involves construction of raised beds and then maintenance of water in the furrows but not on the bed surface. As with plastic film mulching, studies have found this ridge-ditch cultivation significantly reduces methane emissions from paddy fields.[108] Studies also have found that this practice can enhance water use efficiency, improve topsoil temperature and soil aeration, reduce the amount of toxic substances, enhance soil microbial activities, and therefore promote soil nutrient transformation.[109] By improving soil conditions, ridge-ditch cultivation has also been measured to improve rice grain yields by 12.3 percent to 45.8 percent in comparison with traditional cultivation systems.[110]

Both the plastic film mulching system in the hills and ridge-ditch rice production in the lowlands show promise for boosting yields, reducing water use, and reducing greenhouse gas emissions. Yet despite growing adoption by farmers (Figures 6 and 7) and government support, these practices cover only a small portion of the potential in the province. These practices require more intensive labor during rice transplanting, and purchasing the plastic film adds to production costs. These additional expenses can make farmers hesitant to experiment with these practices, especially if they have not yet witnessed the benefit of yield increases.

Figure 7 | **The Area under Plastic Film Mulching in Yanjiang District (Ziyang City, Sichuan Province) Is Rising (hectares)**



Source: Data provided by Shihua Lv, contributing author.

CONCLUSIONS AND RECOMMENDATIONS

There are several water management strategies for significantly reducing methane and therefore total greenhouse gas emissions from rice production. The most common method—practiced extensively in China, Japan, and South Korea—employs one mid-season drawdown of water in the rice paddy. Although practiced because of a broad perception of yield gains, this method also reduces emissions by around 40 percent, according to IPCC's estimate. Alternate wetting and drying (AWD) can reduce emissions even more. While IPCC provides a reduction estimate of roughly 50 percent, U.S. studies suggest that precisely maintained AWD coupled with dry seeding could reduce emissions by 90 percent. In addition, the emerging Chinese experience with raised beds and furrows (with or without plastic mulching) suggests that if farmers could maintain soils at just the precise level of moistness and with just the right combination of water and air, they too could reduce emissions by 90 percent. These different forms of water management can be thought of as a continuum; in general, the more interruptions in flooding and the more air that soils receive, the fewer the emissions.

The bulk of the evidence suggests that appropriate application of these practices should at a minimum avoid depressing yields and can sometimes increase yields. If not practiced carefully, however, drawdowns and AWD can depress yields.

The evidence also suggests a potential water conservation benefit from many forms of improved water management. This benefit is important because many rice-producing regions face growing water shortages. In the Indian state of Punjab, the government has already proposed to reduce rice production area by 40 percent due to water shortages. Savings of 10–40 percent of irrigation water are significant, although it is important to determine if such field-level savings translate into water savings in the broader area.

Despite the benefits—including the yield and water benefits that accrue directly to farmers—there are serious barriers to wide-scale adoption of these practices. These barriers relate to logistics, information, and incentives:

- In most of the Philippines and probably other parts of Asia, it is difficult to sufficiently drain fields during the wet season to conduct full-scale AWD.
- Many farmers—and perhaps most who rely on surface water irrigation systems—do not currently receive a sufficiently reliable supply of water to practice AWD.
- AWD requires well-leveled fields to avoid pockets that dry excessively, and not all rice farms are presently level enough.
- Despite the generally positive evidence so far, proof of AWD's effects on yields, as well as effects on resilience to pests, is insufficient at this time in most of the world's rice producing regions to give farmers confidence they should embrace it. There is no clear explanation of why bed and furrow irrigation increases yields in a few areas in China, but has not been widely embraced elsewhere in China or the world. Science also has not yet determined why a single mid-season drawdown is beneficial for yields in several countries, according to a consensus of farmers and scientists, but researchers in the United States cannot find benefits in tests of that practice.
- In the many locations that cannot practically implement AWD—either because of too much wet season water, insufficiently reliable irrigation, or uneven fields—information about the potential to implement alternative water management strategies, ranging from a single drawdown to direct dry seeding, is lacking.
- Water and electricity subsidies can keep water costs artificially low, removing an important financial incentive for farmers to conserve water through the practices described in this paper.
- Overall, while scientists have been developing a basic understanding of water management in rice and its implications, they have not had the resources or mandate to perform systematic evaluations of practical potential to change water management, or even differential yield effects of management changes.

Based on these assessments, we offer the following recommendations:

Recommendation 1. Research and aid agencies should fund a coordinated and comprehensive engineering assessment of the potential to implement different water management strategies in each of the world's irrigated rice systems.

This investigation should analyze the irrigation system's ability to deliver water and drainage in such a manner that farmers can practice each of the different forms of water management. Where practical obstacles exist, this effort should identify the more cost-effective opportunities for improving irrigation and drainage. Part of these investigations should examine delivery rules, such as those adopted in Bohol (Philippines), which use available distribution capacity to provide a rotating group of farmers with water in such a way as to encourage AWD. This effort will require a combination of funding for a coordinated, international research project that uses similar protocols for analysis, and national funding for the evaluation of local irrigation systems.

Recommendation 2. Research and aid agencies should fund a systematic series of demonstration projects to build the evidence base for how to employ water management systems to maximize direct benefits to farmers (yields, water, and labor).

There should be a systematic combination of water management demonstration projects by farmers and associated research by region to test the yield, disease management, and water conservation implications—as well as production costs of the various forms of water management and methods of addressing any issues that arise. Farmers who participate in the program should be insured against yield losses.

Recommendation 3. Governments need to align incentives for efficient water use, especially in water-stressed areas.

At a minimum, in areas where rice farming is already threatened by insufficient water supplies, water allocation systems should reward farmers who use water more efficiently. In effect, farmers who use less water—and in so doing contribute to conservation of a common pool of water—should receive priority for receiving the water their efforts have conserved when water is short. That common pool may be groundwater or it may be stored surface water. In surface water supplies, systems are typically already in place to monitor water withdrawals, but such systems should be put in place where that is not true or in many groundwater pumping systems.

Recommendation 4. Governments need to reform distortive water and energy subsidies.

In many places where energy is subsidized, many small farmers nevertheless have economic difficulties and depend on these subsidies. But subsidies to small farmers can be provided in ways that do not encourage excess water use. Such reforms and incentives for the efficient use of water are far preferable to the elimination of rice farming in potentially productive areas, or the cancellation of rice farming seasons during unnecessarily severe periods of water shortage.

In addition to these steps, additional incentives or measures will ultimately be required to encourage water management measures where the direct financial benefits to farmers do not justify them.

Improved water management in rice production systems has the potential to significantly reduce agricultural greenhouse gas emissions, while reducing freshwater use, increasing the profitability of rice farming, and maintaining the yields of one of humanity's staple crops. However, much work remains to be done to reliably estimate these benefits and to encourage adoption of these practices at the necessary scale. Nonetheless, improved water management in rice production systems is likely to be an important item on the menu for a sustainable food future.

ENDNOTES

1. All figures in this paragraph come from Searchinger et al. (2013).
2. Authors' calculations from FAO (2014a). In 2011, countries with a total population of 3.75 billion reported rice consumption in excess of 500 calories per day. The world population in 2011 was 7 billion.
3. FAO (2014a).
4. Fischer et al. (2014).
5. Linquist et al. (2012).
6. Roughly 500 million tons are the estimates both of the Food and Agriculture Organization of the United Nations (FAO), which can be found at FAO (2014a), and of the U.S. Environmental Protection Agency (EPA 2012). The EPA estimate uses outdated estimates of the global warming potential of methane. We provide an estimate of 600 million tons based on different estimates of water management practices below.
7. Myhre et al. (2013), Table 8.7. The new IPCC report provides estimates of global warming potential (GWP) for methane alternatively with and without estimated climate feedbacks, and this increased estimate uses the GWP of 34 with feedbacks.
8. There are no published estimates of global nitrous oxide emissions from rice to our knowledge. These calculations are by Xin Zhang, a post-doctoral fellow at Princeton University. The lower estimates applies the IPCC nitrous oxide tier one emission factor for rice of 0.3 percent to estimates of nitrogen fertilizer application to rice from the International Fertilizer Association. Applying the "surplus nitrogen" method set forth in van Groenigen et al. (2010) raises the estimate to 210 million tons.
9. Emissions from rice in five major rice producing countries of Southeast Asia as reported in the most recent National Communication to the UNFCCC (as available in June 2014; see http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php). The percentage of total emissions in Indonesia is low due to very high emissions from deforestation, whereas the high percentage of the total in Myanmar is due to generally low emissions from nonagricultural sectors.

COUNTRY	TOTAL GHG EMISSIONS FROM RICE (GT CO_2E)	PERCENTAGE FROM TOTAL	PERCENTAGE FROM AGRICULTURE SECTOR
Indonesia	34,861	2.53	46.22
Myanmar	5,511	28.36	43.46
Philippines	13,364	13.27	40.34
Thailand	29,940	10.64	57.47
Vietnam	37,101	24.80	57.50

10. As yields grow, so will the production of rice straw, and methane emissions can increase with the incorporation of rice straw into the soil. If rice straw is burned in the field, that will also emit methane. However, the actual amount of GHG emissions depends on how the rice straw is managed, so there is no straightforward correlation for tying quantities of straw to methane emissions at the landscape or national scale.
11. These figures are based on data tables supplied by the authors of Alexandratos and Bruinsma (2012). The 30 percent figure assumes the population growth underlying that study to be only 9 billion by 2050, while the higher figure assumes globally proportionate increases to a population figure of 9.56 billion more recently estimated by the United Nations.
12. Authors' calculations from the tables provided for Alexandratos and Bruinsma (2012). "Historical rate" refers to the annual rate of yield growth (kg/ha) between 1962 and 2006.
13. Ray et al. (2012).
14. Fischer et al. (2014).
15. That estimate is based on an empirical correlation between rice yields and night-time temperature obtained in a long-term field experiment in the Philippines (Peng et al. 2004).
16. Ziska et al. (2009).
17. Van Groenigen et al. (2013).
18. Biochar is a high quality charcoal, which can be made from crop residues. It can help to store carbon in soils and, in some soils, to increase fertility.
19. Setyanto et al. (2000).
20. IPCC (2006).
21. Kumar and Ladha (2011).
22. Kumar and Ladha (2011).
23. The early stages of direct seeding rice require a very shallow flood water cover, so that initial emission rates under direct seeding are typically low (Wassmann et al. 2000). However, the plants take a longer time to grow in the field, increasing flood duration. (Young rice plants grown in a nursery are also flooded but typically occupy only 15–20 percent of the rice area; see http://www.knowledgebank.irri.org/erice-production/II.5_Nursery_systems.htm.)
24. Pittelkow et al. (2014).
25. Itoh et al. (2011).
26. Siopongco et al. (2013).
27. Joshi et al. (2013), Table 3.
28. IPCC (2006).
29. Linquist et al. (2014).
30. Joshi et al. (2013).
31. Sander et al. (2014).
32. Yan et al. (2006). That paper took estimates of mid-season drainages from a report for the Asian Development Bank.
33. Li et al. (2002).

34. Authors' calculations based on FAO (2014a). In 2013, China (30 Mha), Japan (2 Mha), and South Korea (1 Mha) together accounted for 33 Mha of rice paddy area, or 20 percent of the global total of 165 Mha.
35. Bouman and Tuong (2001).
36. Rejesus et al. (2011).
37. Lampayan (2013).
38. Kuerschner et al. (2010).
39. Water Technology Centre (2009), World Bank (2006).
40. Siopongco et al. (2013).
41. Parthasarathi et al. (2012).
42. The Global Commission on the Economy and Climate (2014).
43. According to Gassert et al. (2013), 29 percent of the world's rice is grown in areas facing high to extremely high levels of water stress.
44. Li et al. (2014), Bouman et al. (2007a).
45. Hafeez et al. (2008).
46. Authors' calculations from FAO (2014a).
47. Directorate of Economics and Statistics (2012).
48. Government of Tamil Nadu (2009).
49. Commissionerate of Agriculture (2012).
50. Balakrishnan and Vasanthakumar (2010).
51. Rajkishore (2013).
52. Palanisami and Paramasivam (2000).
53. World Bank (2006).
54. Water Technology Centre (2009).
55. World Bank (2006).
56. In theory, different states in India assign some irrigation charges, but they are rarely if ever collected by revenue officials and so in effect become free (Central Water Commission 2010).
57. Government of Punjab (2013).
58. Central Water Commission (2010), Department of Agriculture (2012).
59. Chauhan et al. (2012).
60. Mahajan et al. (2013).
61. Mahajan et al. (2013).
62. Chaba (2013).
63. Pathak et al. (2012).
64. "Brown manuring" refers to seeding rice and *Sesbania* (a nitrogen-fixing plant) together, then applying a herbicide to turn the *Sesbania* into a weed-suppressing mulch.
65. Bhatia et al. (2013).
66. Personal communication, A. K. Jain, Department of Soil & Water Engineering, Punjab Agricultural University, Ludhiana, India.
67. Singh and Kumar (2010).
68. Kaur et al. (2011).
69. Vashishtha and Gupta (2006).
70. Committee for Formulation of Agriculture Policy for Punjab State (2013).
71. FAO (2014a).
72. Pinoy Rice Knowledge Bank (2014).
73. IRRI authors' calculations. The calculation is applied in two rice ecosystems (irrigated and rainfed) for two seasons. Dry season runs from January to June and wet season from July to December. Emission and scaling factors follow the guidelines in IPCC (2006). An emission factor of 1.3 kg methane / hectare / day for 100 days (which corresponds to the average maturity of rice plants) is used. Scaling factors of 1.0 and 0.28 are used for irrigated and rainfed rice, respectively. In Figure 2, the assumption is that AWD is applied in irrigated rice during dry season only. The scaling factor for multiple aeration (0.52) is used to reflect the emissions from rice under AWD management.
74. FAO (2014b).
75. FAO (2008), percentage referring to the year of 1992.
76. Siopongco et al. (2013).
77. Dawe (2005).
78. Hafeez et al. (2008).
79. Sander et al. (2014).
80. Lampayan et al. (2009).
81. Mariano et al. (2012).
82. FAO (2014b).
83. Rejesus et al. (2011).
84. Rejesus et al. (2011).
85. Belder et al. (2004), Lampayan et al. (2009), Tabbal et al. (2002).
86. Hafeez et al. (2008).
87. Sibayan et al. (2010), Rejesus et al. (2011).
88. Rejesus et al. (2013).
89. Rejesus et al. (2013).
90. Authors' calculations from FAO (2014a).
91. USDA (2014).
92. Linquist et al. (2014).
93. This is based on work by Linquist et al. (2014).
94. Pittelkow et al. (2014).
95. Linquist et al. (2014).
96. California Rice Research Board (2014).
97. Linquist et al. (2014).
98. More information can be found at: <http://americancarbonregistry.org/>.
99. Authors' calculations from FAO (2014a).
100. Zhang et al. (2013a, b), Liu et al. (2013), Zhang and Li (2003).
101. Authors' calculations.
102. Zhang et al. (2013b).
103. Fan et al. (2005), Li et al. (2007), Liu et al. (2003), Zeng (2012).
104. Li et al. (2004), Li et al. (2007).
105. Lu et al. (2007).
106. S. Lv (contributing author, unpublished data) estimated plastic film costs of 750 RMB, but savings in pesticides and fertilizer input of 657 RMB, plus labor savings of 2,700 RMB. Zeng and Liu (2012) found similar savings.
107. Wei et al. (2000), Wang et al. (2002).
108. Cai et al. (2000).
109. Wei et al.(2000), Wang et al.(2002), Wang et al.(2012).
110. Wang (2008).

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