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The **Diverse Benefits** of **Alternate Wetting and Drying** (AWD)

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Rice is a staple for half the world's population, thus its impact on land and water use is immense. Standard production practices using continuous flooding (CF) are resource intensive and contribute significant global methane emissions. The technique of alternate-wetting-drying (AWD) uses a more controlled irrigation strategy that can significantly reduce methane emissions as well as water use and pumping costs. These three established benefits of AWD have been well documented in previous papers (see Overview of AWD[1]). Aside from these primary benefits, recent literature suggests there are many potential secondary benefits that have yet to be fully reviewed. These co-benefits and their site-specific conditions or limitations are reviewed in this paper.

Production benefits

Reduced flooding using AWD can improve soil properties for mechanization and diversified crop rotation, making rice a more suitable crop for rotation with upland (non-rice) crops. This is increasingly important as paddy-upland systems expand globally[2]. Additionally, the technologies that accompany AWD (i.e., irrigation upgrades, moisture monitoring and laser land leveling or LLL) bring improved control over crop growth, uniformity, and field operations.

How?

1. **Soil structure and diversified crop rotation.** Poor soil structure from puddling and continuous flooding is the greatest challenge to rotating rice with other crops[3]. Reduced flooding using AWD may improve soil structure for upland crops following rice due to increased soil aggregation and macroporosity[4]. Effects on soil structure may be most apparent at lower depths from deeper root accumulation and improved aeration. Improved soil structure may also facilitate the move to dry-direct seeding and aerobic rice[5].

   Site-specifics and limitations:
   AWD is most effective in lowland finer textured soils that hold moisture[6]. These soils are also particularly difficult to rotate between paddy rice and upland crops like maize, yet they often have the greatest potential for fertile, continuous cropping[7]. The benefits of AWD rice and upland crop rotation are greatest under a reduced plow pan density, high soil organic matter, and moderately acidic pH[8]. Higher pH soils may experience increased salinity or soil structure problems upon drying with AWD[9]. Gradual improvement to soil structure using AWD and residue incorporation while increasing drainage/percolation could mitigate these problems[10]. Like no-till practices, long-term improvement to soil using AWD and residue may take several seasons or experience an initial "yield drag." Soil types most suitable for AWD may also be best for aerobic rice[11].

2. **Mechanization.** Improved soil structure (i.e., macroporosity and aggregation) from AWD may provide better tilth, traction, and soil load bearing capacity[12]. This improves machinery efficiency, along with the flexibility of equipment types (a limiting factor in current rice mechanization and its adoption).

   Site-specifics and limitations:
   As with crop rotation problems, heavy clay soils can be most difficult for mechanization when wet. Additional limitations to mechanization include small farm sizes and poor access to equipment.

3. **Soil moisture control.** Improved irrigation management is the principle of AWD. Irrigation equipment upgrades along with the use of LLL and field water level tubes to regulate soil moisture can aid in more efficient and timely harvesting, planting, application of fertilizer, and meeting of crop water needs[13]. This can improve yields, crop turnaround potential, and resiliency to weather volatility[14].

   Site-specifics and limitations:
   Optimal soil moisture control requires level fields. Access to reliable season-long irrigation water is a limitation to AWD adoption and will require improvements to infrastructure and investments at the regional and farm level[15].

Yield

Results of some 60 peer-reviewed studies suggest that safe AWD (maintaining a 15 cm below soil surface water level threshold) does not reduce yields if implemented correctly and may potentially increase yields under specific conditions[16]. Still, without proper management the risk of drought stress is increased in AWD. Although current rice cultivars are severely sensitive to water stress, improved breeding for aerobic conditions may eventually raise yield potentials above that of CF due to the benefits of aeration on soil physicochemical properties and plant morphology. Studies on biotic stressors (pests, disease, weeds) have shown that AWD may reduce some pests, albeit increasing others. Certainly, some pests adapted to millennia of flooded culture are disrupted in aerobic environments. It is foreseeable that the rotation between flooded and aerobic varieties may provide an important strategy towards IPM in the future[17].

How?

1. **Pest, disease and weed management.** A shift in pest, disease, and weed types is expected when switching from CF to AWD. Although AWD can effectively control golden apple snail, brown plant hopper, false smut, algae and other aquatic weeds, it can increase the occurance of non-aquatic weeds, rice blast, bacterial leaf blight, and root-knot nematode[18]. Certain disease reduction from AWD has been recorded from reduced humidity within the crop canopy, and improved systemic resistance[19]. AWD may increase pathogen survival and transfer between rotation of related aerobic crops[20]. Improved knowledge of IPM is likely necessary under AWD.

   Site-specifics and limitations:
   Fields with a known history of the issues associated with AWD require farmer discretion of water-pest relationships. AWD increases the need for knowledge-intensive farm management with the use of new or alternative practices and equipment.

2. **Root and tiller development.** Rice root depth/density is often enhanced with AWD, which can equate to better drought, disease, and lodging resistance, as well as increased nutrient and water uptake[21]. This is due to improved soil structure for root exploration and oxygenation[22]. AWD can also increase effective tiller development, suggesting seeding rate can be reduced, and yield increased[23].

   Site-specifics and limitations:
   Deeper rooting due to reduced compaction and plow pan density may be most beneficial in areas with root-accessible water tables that are prone to drought or wind lodging[24]. Clay soil types prone to compaction or anoxia may also benefit most.

3. **Phytotoxin removal.** Increased aerobic periods using AWD can reduce phytotoxins that accumulate from CF and anoxia such as phenolic acids, hydrogen sulphide, and excess iron and manganese[25].

   Site-specifics and limitations:
   Low percolation rates under CF and residue incorporation are known causes of phytotoxin buildup. Limited percolation along with poor irrigation water can also increase salinity

and alkalinity. Although AWD may increase salinity in the short-term it may reduce long-term salt evapoconcentration by reducing irrigation input and with residue incorporation this can further ameliorate the effect on crops.

4. **Soil fertility and quality.** Although AWD may reduce the availability of certain nutrients like phosphorous and calcium compared to CF, it can enhance fertility in some soils by increasing zinc and nitrogen uptake, and by increasing mineralizable nutrients from organic matter decomposition[26]. Increased organic matter decomposition from AWD reduces the need for complete removal of crop residue (a standard practice due to its impediment to planting)[27]. Although incorporation of crop residue can increase methane emissions in CF systems, this is minimized in more aerobic soils utilizing AWD or upland crop rotations. The additional benefits of residue on soil quality and soil carbon make residue incorporation advantageous for non-CF systems[28].

   Site-specifics and limitations:
   Nutrient deficiencies for a given soil will help guide irrigation management given the known relationship of nutrient availability and flooding. Lab nutrient analysis can suggest the potential gain or decline to soil fertility for a specific soil under aerobic conditions. As a general principle, fertilizer N and P requirements could be higher for rice grown on aerobic soil than on submerged soil. A higher need for accurate N fertilizer application can arise from lower microbial nitrogen fixation. Although denitrification and N leaching may occur if fertilizer is improperly applied under AWD, total N losses are normally negligible due to the increase in available forms of nitrogen and overall increase in nitrogen use efficiency[29]. Zn availability is normally increased under aerobic regimes on acid soils, but high pH soils may experience Zn and Fe reduction[30]. Although studies show that the conversion from flooded to aerobic soils reduces SOC quantity and ability of soils to store carbon, there is strong evidence that aerobic regimes improve the quality of plant-beneficial SOC fractions and that total SOC can increase given proper residue management[31].

5. **Soil health.** Soil microbial and invertebrate activity in the root zone may be increased under aerobic conditions leading to enhanced nutrient cycling and biological tillage[32]. This allows the recycling of organic nutrients for proceeding crops that are often locked up in submerged soils. Reduced flooding is known to increase soil macrofauna such as earthworms that improve soil physicochemical properties[33].

   Site-specifics and limitations:
   Residue incorporation in combination with AWD can improve microbial activity and diversity compared with CF[34]. Increased microbial activity may require additional fertilizer inputs initially due to immobilization and reduced biological nitrogen fixation from algae. Benefits from residue incorporation normally occur after several seasons.

Human health

Flooded rice is associated with increased mosquito and water borne diseases[35]. Additionally, AWD has been shown to improve grain quality – a concern for millions of people in developing Asian countries.

How?

1. **Mosquito and water borne diseases.** The use of intermittent flooding periods of less than one week using AWD can disrupt mosquito life cycles during their normal two week aquatic larval stage[36]. Snails are also important vectors of disease that can be reduced under AWD along with other water transmitted pathogens. Regions with high risk of malaria, schistosomiasis, Japanese encephalitis, dengue, and leptospirosis may consider AWD as a public health strategy.

2. **Grain quality.** Zinc deficiency affects a third of the global population, mostly in high rice consuming regions of Southeast Asia. More aerobic regimes using AWD can effectively increase grain zinc content[37]. Rice is also a primary source of dietary heavy metal exposure[38]. Aerobic conditions reduce the availability of arsenic and mercury to plants[39], however, an increase in cadmium uptake is also possible[40]. Reduced irrigation inputs with AWD can also reduce the deposition of other source-water contaminants in paddy soils.

   Site-specifics and limitations:
   Risk of heavy metal accumulation for a given environment will help guide irrigation and rotation management for risk mitigation. Areas near municipal waste are prone to cadmium contamination. High levels of naturally occurring arsenic are known to occur in deep well water in some parts of South Asia. Acidic soils or fine textured wetland sediments increase the risk of heavy metal crop uptake[41].

Environment

Asia is increasingly vulnerable to environmental issues and land use competition, which inherently involves rice. Although rice can have a low environmental impact compared to other cropping systems, it is an important part of land and water use competition with biodiversity in some of the world's most sensitive ecosystems. Rice farming uses almost 50% of total water consumption in Asia and contributes to land, air and water quality degradation[42]. In some cases, AWD can reduce this impact.

How?

1. **Erosion/runoff and ecosystems.** CF practices can increase overland flow erosion, which is a significant source of agrochemical pollution and nutrient-bound sediment in waterways[43]. Compared to CF, AWD has been shown to reduce surface runoff of nitrogen and phosphorous by 30%, and pesticides by 89% in some studies[44]. AWD could further reduce runoff in upland crops after rice by facilitating residue incorporation, soil structure improvement and reduced tillage[45]. Additionally, reducing water use with AWD would increase water available to off-farm ecosystems[46].

   Site-specifics and limitations:
   Strong monsoonal rains can raise paddy flood levels beyond bunds. Cascade irrigation promotes sediment and nutrient loss towards basins. Leaching of pollutants in solution, especially nitrate, may be increased under AWD if bypass water losses are increased from cracking[47]. N losses can be avoided in high CEC soils and with proper fertilizer and irrigation application on cracked soil. Reduced tillage may be most successful in loamy or high organic matter soils.

2. **Straw burning.** Straw burning is a significant source of air pollution and greenhouse gas emissions from Asia. Rice straw is often burned and not incorporated due to labor constraints and the impediment to planting of following crops[48]. Increased aeration from AWD improves straw decomposition and the ability to incorporate residue without hindrance to field preparation[49].

   Site-specifics and limitations:
   Disease occurance may increase from incorporating residues, as opposed to burning or removing. Straw incorporation increases methane emissions and can reduce rice yields under continuously flooded culture. Coarse textured soils may benefit the most from straw incorporation and improved aerobic decomposition. Combine harvesters can aid in returning residues and reducing labor cost.

Socioeconomics

Rice is the staple crop of the developing world and an important part of its socioeconomic challenges. Methods such as AWD that increase farm efficiency, and reduce resource competition can be effective socioeconomic solutions.

How?

1. **Farm profits.** A primary benefit of AWD is the reduced pumping costs from lower water use. This often equates to improved farm profits, although this is site-specific depending on pump fees. As water scarcity increases, AWD will be of increasing value.

   Site-specifics and limitations:
   Studies show that water payment schemes that incentivize water saving are critical in the success of AWD. Areas with fixed or flat-rate seasonal pump costs may not benefit from AWD. Even in areas where AWD could improve yields, reduced pump costs will be the primary driver of adoption given that they often account for 25% of production costs[50].

2. **Water competition.** Reduced water consumption using AWD has been shown to reduce upstream-downstream water conflicts and improve social equity[51].

3. **Climate change adaptation.** CF and rainfed rice cultivation is highly dependent on seasonal water supply that is increasingly hard to predict. Properly implemented AWD with improved irrigation systems can help farmers adapt to less predictable weather and drought[52].

4. **Impacting low-income sectors.** As a low-cost and easy to implement technology, AWD can improve livelihoods especially for low-income smallholders where yields or farm profits can be improved[53].

Conclusion and future research

Although continuously flooded rice has proven to be sustainable in terms of yields and soil quality for rice only cropping, changing resource limitations require a paradigm shift in rice farming. AWD is an effective solution to sustaining or improving rice yields in the future under increasing water limitations and the need to intensify land productivity using mechanization and crop rotation. In addition to the core benefits of AWD (reduced emissions, water use, and pump costs), studies show that additional co-benefits exist that can improve agronomic, human health, environmental, and socio-economic factors in rice production. Successful adoption of AWD and its benefits will require discretion of site-specific conditions such as climate, soil type, pests, rotation type and irrigation access. Understanding these site-specifics and the potential trade-offs of more aerobic regimes in rice will require additional research. Without an exhaustive list, research is needed on the co-benefits of AWD regarding:

- The potential of improved aerobic or AWD rice varieties in the future regarding yield/water tradeoffs, as well as pests and disease.
- Environmental impacts of water conservation from AWD on natural resource economics, ecosystem services, human health, and biodiversity.
- Effects of AWD on gender equity and labor productivity
- The yield of aerobic crops used in rotation with AWD vs. flooded rice under varying soil types and environments.
- Soil organic carbon quantity vs. quality comparing anaerobic and aerobic decomposition, along with optimized residue management for AWD.
- Rice-aerobic crop rotation as a pest management strategy.
- Effects of long-term AWD on soil salinity.

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