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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.

References

1

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, 203, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

2

Timsina, J., Buresh, R., Dobermann, A., & Dixon, J. (2011). *Rice-maize systems in Asia: current situation and potential*. CIMMYT/IRRI

3

(IRRI) International Rice Research Institute, Los Baños, Philippines. (1985). Soil Physics and Rice, pp. 217-234. https://doi.org/10.1017/S001447970000123X

Zhou, W., Lv, T. F., Chen, Y., Westby, A. P., & Ren, W. J. (2014). Soil physicochemical and biological properties of paddy-upland rotation: A review. *Scientific World Journal*, 2014. https://doi.org/10.1155/2014/856352

Kriesemer, S. K. (2013). Rice cropping systems and resource efficiency, 41. Retrieved from https://www.giz.de/fachexpertise/downloads/giz2013-en-study-rice-cropping-sys-low-res.pdf

Yusuf, Ali M., Waddington, S.R., Timsina, J., Hodson, D. & Dixon, J. (2009). Maize-rice cropping systems in Bangladesh: Status and research needs. J. Agr. Sci. Tech., USA, 3(6):35-53 (Serial No.19).

D Sayre, K., & Hobbs, P. (2004). *The Raised-Bed System of Cultivation for Irrigated Production Conditions*. https://doi.org/10.1201/9780203026472.ch20

Gopal, C., & Direct, R. (n.d.). production technology and weed management in rice based systems . Technical Bulletin . International Maize and Wheat Improvement Center , New Delhi India . pp 28 . *South Asia*.

Ritzema, H. P., Satyanarayana, T. V., Raman, S., & Boonstra, J. (2008). Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agricultural Water Management*, 95(3), 179–189. https://doi.org/10.1016/j.agwat.2007.09.012

Jat, R. K., Gopal, R., Jat, M. L., Singh, R. G. Y., & Kumar, M. (n.d.). Productivity and carbon based sustainability index of maize under contrasting tillage practices for rice-maize production systems of the eastern Indo-Gangetic plains.

Humphreys, E., Meisner, C., Gupta, R., Timsina, J., Beecher, H. G., Lu, T. Y., … Thompson, J. A. (2005). Water Saving in Rice-Wheat Systems. *Plant Production Science*, 8(3), 242–258. https://doi.org/10.1626/pps.8.242

Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Kumar, V., Kumar, V., & Sharma, P. K. (2011). Effect of Tillage and Crop Establishment Methods on Physical Properties of a Medium-Textured Soil under a Seven-Year Rice−Wheat Rotation. *Soil Science Society of America Journal*, 75, 1851–1862. https://doi.org/10.2136/sssaj2010.0362

Singh, Y., & Sidhu, H. S. (2014). Management of cereal crop residues for sustainable rice-wheat production system in the Indo-Gangetic Plains of India. *Proceedings of the Indian National Science Academy*, 80(1), 95–114. https://doi.org/10.16943/ptinsa/2014/v80i1/55089

Humphreys, E., Meisner, C., Gupta, R., Timsina, J., Beecher, H. G., Lu, T. Y., … Thompson, J. A. (2005). Water Saving in Rice-Wheat Systems. *Plant Production Science*, 8(3), 242–258. https://doi.org/10.1626/pps.8.242

4

Pires, L. F., Cooper, M., Cássaro, F. A. M., Reichardt, K., Bacchi, O. O. S., & Dias, N. M. P. (2008). Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. *CATENA*, 72(2), 297–304. https://doi.org/10.1016/J.CATENA.2007.06.003

Fang, H., Zhou, H., Norton, G., Price, A., Raffan, A., Mooney, S., . . . Hallett, P. (2018). Interaction between contrasting

rice genotypes and soil physical conditions induced by hydraulic stresses typical of alternate wetting and drying irrigation of soil. *Plant and Soil*, 430(1-2), 233-243

Kriesemer, S. K. (2013). Rice cropping systems and resource efficiency, 41. Retrieved from https://www.giz.de/fachexpertise/downloads/giz2013-en-study-rice-cropping-sys-low-res.pdf

Tripathi, R. P., Sharma, P., & Singh, S. (2005). Tilth index: an approach to optimize tillage in rice–wheat system. *Soil and Tillage Research*, 80(1), 125–137. https://doi.org/https://doi.org/10.1016/j.still.2004.03.004

Mondal, S., Kumar, S., Haris, A. A., Dwivedi, S. K., Bhatt, B. P., & Mishra, J. S. (2016). Effect of different rice establishment methods on soil physical properties in drought-prone, rainfed lowlands of Bihar, India. *Soil Research*, 54(8), 997–1006. Retrieved from https://doi.org/10.1071/SR15346

(IRRI) International Rice Research Institute, Los Baños, Philippines. (1985). Soil Physics and Rice, pp. 217-234. https://doi.org/10.1017/S001447970000123X

Chen, S., Xi Zheng, Wang, D., Chen, L., Xu, C., and Zhang, C. (2012). "Effect of Long-

Term Paddy-Upland Yearly Rotations on Rice (Oryza sativa) Yield, Soil Properties, and Bacteria Community Diversity," *The Scientific World Journal*, vol. 2012, Article ID 279641, 11 pages, https://doi.org/10.1100/2012/279641.

Zhou, W., Lv, T. F., Chen, Y., Westby, A. P., & Ren, W. J. (2014). Soil physicochemical and biological properties of paddy-upland rotation: A review. *Scientific World Journal*, 2014. https://doi.org/10.1155/2014/856352

Linh, T. B., Sleutel, S., Vo Thi, G., Le Van, K., & Cornelis, W. M. (2015). Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture. *Soil and Tillage Research*, 154, 44–52. https://doi.org/https://doi.org/10.1016/j.still.2015.06.011

5

Kumar, V., & Ladha, J. K. (2011). *Direct Seeding of Rice. Recent Developments and Future Research Needs. Advances in Agronomy* (1st ed., Vol. 111). Elsevier Inc. https://doi.org/10.1016/B978-0-12-387689-8.00001-1

(PDF) *Identification of Suitable Area for Aerobic Rice Cultivation in the Humid Tropics of Eastern India*. (n.d.). Retrieved from https://www.researchgate.net/publication/270396797_Identification_of_Suitable_Area_for_Aerobic_Rice_Cultivation_in_the_Humid_Tropics_of_Eastern_India

Gathala, M., Yadav, S., Abdul Mazid, M., Humphreys, E., Ahmed, S., Krupnik, T., . . . McDonald, A. (2014). *Guidelines for Dry Seeded Aman Rice (DSR) in Bangladesh*. IFAD, CSISA, IRRI, CIMMYT joint publication.

Kato, Y., & Katsura, K. (2014). Rice Adaptation to Aerobic Soils: Physiological Considerations and Implications for Agronomy. *Plant Production Science*, 17(1), 1-12.

6

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, 203, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

7

Bañoc, D., Yamauchi, A., Kamoshita, A., Wade, L., & Pardales, J. (2000). Dry Matter Production and Root System Development of Rice Cultivars under Fluctuating Soil Moisture. *Plant Production Science*, 3(2), 197-207.

8

Vial, L. K. (2007). Aerobic and (AWD) Rice Systems, (February), 43. Retreived from https://nuffieldinternational.org/live/Report/AU/2006/leigh-vial

9

Alam, MK., Islam, MM., Salahin, N., Hasanuzzaman, M. (2014). Effect of tillage practices on soil properties and crop productivity in wheat mungbean-rice cropping system under subtropical climatic conditions. Science World J 8:1-15

Song, K., Yang, J., Yong, X., Weiguang, L., Zheng, X., Pan, J. (2016). Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. Scientific Reports volume 6, Article number: 36602 doi:10.1038/srep36602

10

Biggs, T. W., & Jiang, B. (2009). Soil Salinity and Exchangeable Cations in a Wastewater Irrigated Area, India. *Journal of Environment Quality*, 38(3), 887. https://doi.org/10.2134/jeq2008.0247

11

(PDF) Identification of Suitable Area for Aerobic Rice Cultivation in the Humid Tropics of Eastern India. (n.d.). Retrieved from https://www.researchgate.net/publication/270396797_Identification_of_Suitable_Area_for_Aerobic_Rice_Cultivation_in_the_Humid_Tropics_of_Eastern_India

Kato, Y., & Katsura, K. (2014). Rice Adaptation to Aerobic Soils: Physiological Considerations and Implications for Agronomy. *Plant Production Science*, 17(1), 1-12.

12

Keen, A., Hall, N., Soni, P., Gholkar, M. D., Cooper, S., & Ferdous, J. (2013). A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production. *Journal of Terramechanics*, 50(1), 45–62. https://doi.org/https://doi.org/10.1016/j.jterra.2012.08.001

Pires, L. F., Cooper, M., Cássaro, F. A. M., Reichardt, K., Bacchi, O. O. S., & Dias, N. M. P. (2008). Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. *CATENA*, 72(2), 297–304. https://doi.org/10.1016/J.CATENA.2007.06.003

Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Kumar, V., Kumar, V., & Sharma, P. K. (2011). Effect of Tillage and Crop Establishment Methods on Physical Properties of a Medium-Textured Soil under a Seven-Year Rice−Wheat Rotation. *Soil Science Society of America Journal*, 75, 1851–1862. https://doi.org/10.2136/sssaj2010.0362

Meryl Richards, B. O. S. (2014). Practice Brief CSA, AWD in Irrigated Rice. *Journal of AHIMA/American Health Information Management Association*, suppl 2p; quiz 49-50.

Kriesemer, S. K. (2013). Rice cropping systems and resource efficiency, 41. Retrieved from https://www.giz.de/fachexpertise/downloads/giz2013-en-study-rice-cropping-sys-low-res.pdf

13

Aryal, J., Mehrotra, M., Jat, M., & Sidhu, H. (2015). Impacts of laser land leveling in rice–wheat systems of the north–western indo-gangetic plains of India. *Food Security*, 7(3), 725-738.

Jafari-Talukolaee, M.; Darzi Naftchali, A.; Zare-Parvariji, L.; Ahmadi, M.Z. (2018) Investigating long-term effects of subsurface drainage on soil structure in paddy fields. Soil Tillage Res. 177, 155–160. https://doi.org/10.1016/j.still.2017.12.012

Darzi-Naftchali, A., Ritzema, H., Karandish, F., Mokhtassi-Bidgoli, A., Ghasemi-Nasr, M., (2017). Alternate wetting and drying for different subsurface drainages systems to improve paddy yield and water productivity in Iran. Agric. Water Manage. 193, 221–231. https://doi.org/10.1016/j.agwat.2017.08.018

Wichelns, D. (2016). Managing Water and Soils to Achieve Adaptation and Reduce Methane Emissions and ArsenicContamination in Asian Rice Production. https://doi.org/10.3390/w8040141

Jafari Talukolaee, M., Darzi Naftchali, A., Zare Parvariji, L., & Ahmadi, M. Z. (2018). Investigating long-term effects of subsurface drainage on soil structure in paddy fields. *Soil and Tillage Research*, 177, 155–160. https://doi.org/10.1016/J.STILL.2017.12.012

(IRRI) International Rice Research Institute, Los Baños, Philippines. (1985). Soil Physics and Rice, pp. 217-234.https://doi.org/10.1017/S001447970000123X

14

Zhang, H., Xue, Y., Wang, Z., Yang, J., & Zhang, J. (2009). An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. *Crop Science*, 49(6), 2246–2260. https://doi.org/10.2135/cropsci2009.02.0099

Bañoc, D. M., Yamauchi, A., Kamoshita, A., Wade, L. J., & Pardales, J. R. (2000). Dry Matter Production and Root System Development of Rice Cultivars under Fluctuating Soil Moisture. *Plant Production Science*, 3(2), 197–207. https://doi.org/10.1626/pps.3.197

15

Mushtaq, S., Khan, S., Hafeez, M., & A. Hanjra, M. (2009). *Does reliability of water resources matter in the adoption of water-saving irrigation practices? A case study in the Zhanghe irrigation system, China*. Water Policy (Vol. 11). https://doi.org/10.2166/wp.2009.033

16

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, 203, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Li, Z., Azeem, S., Zhang, Z., Li, Z., Zhao, H., & Lin, W. (2016). Promising Role of Moderate Soil Drying and Subsequent Recovery Through Moderate Wetting at Grain-Filling Stage for Rice Yield Enhancement. *Journal of Plant Growth Regulation*, 35(3), 838-850.

Zhang, H., Xue, Y., Wang, Z., Yang, J., & Zhang, J. (2009). An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. *Crop Science*, 49(6), 2246-2260.

Kürschner, E., & Henschel, C. (2010). *Water Saving in Rice Production–Dissemination, Adoption and Short Term Impacts of Alternate Wetting and Drying (AWD) in Bangladesh. Series of the Department of Rural Development 241*. Retrieved from http://agriwaterpedia.info/images/1/16/SLE_(2010)_Water_Saving_in_Rice_Production.pdf

17

Shrestha, S., Deb, P., & Bui, T. T. T. (2016). Adaptation strategies for rice cultivation under climate change in Central Vietnam. *Mitigation and Adaptation Strategies for Global Change*, 21(1), 15–37. https://doi.org/10.1007/s11027-014-9567-2

18

Davies W. J., Zhang J., Yang J., and Dodd I. C.. (2011). Novel crop science to improve yield and resource use efficiency in water-limited agriculture. J. Agricult. Sci. 149:123–131

Zhao, D., & Kumar, A. (2016). Technical Assistance Consultant ' s Report Regional : Development and Dissemination of Climate-Resilient Rice Varieties for Water-Short Areas of South Asia and Southeast Asia (Financed by the Climate Change Fund and the Government of, (June).

Dodd, I. C., Puértolas, J., Huber, K., Pérez-Pérez, J. G., Wright, H. R., & Blackwell, M. S. A. (2015). The importance of soil drying and re-wetting in crop phytohormonal and nutritional responses to deficit irrigation. *Journal of Experimental Botany*, 66(8), 2239–2252. Retrieved from http://dx.doi.org/10.1093/jxb/eru532

Vial, L. K. (2007). Aerobic and (AWD) Rice Systems, (February), 43. Retreived from https://nuffieldinternational.org/live/Report/AU/2006/leigh-vial

Arnaoudov, V. (2015). Adaptation and mitigation initiatives in Philippine rice cultivation.

New York:United Nations Development Programme.

T Chapagain, A Riseman, E Yamaji. (2011). Achieving more with less water: alternate wet and dry irrigation (AWDI) as an alternative to the conventional water management practices in rice farming. - Journal of Agricultural Science

Grierson, W., Soule, J., & Kawada, K. (1982). *Beneficial Aspects of Physiological Stress* (Vol. 4). https://doi.org/10.1007/978-1-349-06519-6_8

A. Mostajeran and V. Rahimi-Eichi, (2008). Drought Stress Effects on Root Anatomical Characteristics of Rice Cultivars (Oryza sativa L.). Pakistan Journal of Biological Sciences, 11: 2173-2183. DOI: 10.3923/pjbs.2008.2173.2183

19

Brooks, S. Anders, M. & Yeater, K. (2010). Effect of Furrow Irrigation on the Severity of False Smut in Susceptible Rice Varieties. Plant Disease. 94. 10.1094/PDIS-94-5-0570.

Dodd, I. C., Puértolas, J., Huber, K., Pérez-Pérez, J. G., Wright, H. R., & Blackwell, M. S. A. (2015). The importance of soil drying and re-wetting in crop phytohormonal and nutritional responses to deficit irrigation. Journal of Experimental Botany, 66(8), 2239–2252. Retrieved from http://dx.doi.org/10.1093/jxb/eru532

Jia, Q., Lv, B., Guo, M. et al. (2015). Effect of rice growth stage, temperature, relative humidity and wetness duration on infection of rice panicles by Villosiclava virens . Eur J Plant Pathol 141, 15–25. Retrieved from https://doi.org/10.1007/s10658-014-0516-4

Pineda, J. B., Colmenárez, O., Gutiérrez, L., & Aranguren, W. (2006). Inoculum distribution of rice pathogenic fungi in Payara, Portuguesa state. Effect of temperature and relative humidity. Fitopatología Venezolana 19(2), 32-38.

Zhang, Z. C., Li, H. W., Chen, T. T., Wang, X. M., Wang Z. Q., & Yang J. C. (2011). Effect of furrow irrigation and alternate wetting and drying irrigation on grain yield and quality of rice. Scientia Agricultura Sinica 44(24) 4988-4998.

Zhao, D. L., Atlin, G. N., Amante, M., Cruz, M. T. S., & Kumar, A. (2010). Developing aerobic rice cultivars for water-short irrigated and drought-prone rainfed areas in the tropics. *Crop Science*, 50(6), 2268–2276. https://doi.org/10.2135/cropsci2010.10.0028

20

Van Buyten, E., Banaay, C., Vera Cruz, C., & Höfte, M. (2013). Identity and variability of Pythium species associated with yield decline in aerobic rice cultivation in the Philippines. *Plant Pathology*, 62(1), 139-153.

21

Arnaoudov, V. (2015). Adaptation and mitigation initiatives in Philippine rice cultivation. New York:United Nations Development Programme.

Paul, P., & Rashid, M. A. (2013). Refinement of Alternate Wetting and Drying Irrigation Method for Rice Cultivation. *Bangladesh Rice Journal*, 17, 37–41.

Dong, N. M., Brandt, K. K., Sørensen, J., Hung, N. N., Hach, C. Van, Tan, P. S., & Dalsgaard, T. (2012). Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. Soil Biology and Biochemistry, 47(August), 166–174. https://doi.org/10.1016/j.soilbio.2011.12.028

Zhang, H., Xue, Y., Wang, Z., Yang, J., & Zhang, J. (2009). An Alternate Wetting and Moderate Soil Drying Regime Improves Root and Shoot Growth in Rice. *Crop Science*, 49, 2246–2260. https://doi.org/10.2135/cropsci2009.02.0099

Yamaguchi, T., Luu, M. T., Minamikawa, K., & Yokoyama, S. (2017). Compatibility of Alternate Wetting and Drying Irrigation with Local Agriculture in An Giang Province , Mekong Delta , Vietnam, 117–127.

Zhao, D., & Kumar, A. (2016). Technical Assistance Consultant ' s Report Regional : Development and Dissemination of Climate-Resilient Rice Varieties for Water-Short Areas of South Asia and Southeast Asia (Financed by the Climate Change Fund and the Government of, (June).

Mao Zhi (2000). Water-efficient irrigation and environmentally sustainable irrigated rice production in

China. Paper for ICID annual meeting. International Commission on Irrigation and Drainage (http://www.icid.org/wat_mao.pdf) lodging pests disease (Yi, 1999),

Zhu, J., Liang, J., Xu, Z., Fan, X., Zhou, Q., Shen, Q., & Xu, G. (2015). Root aeration improves growth and nitrogen accumulation in rice seedlings under low nitrogen. AoB PLANTS, 7, plv131-plv131. Retrieved from http://dx.doi.org/10.1093/aobpla/plv131

Yang, C., Yang, L., Yan, T., & Ouyang, Z. (2004). [Effects of nutrient and water regimes on lodging resistance of rice]. *Ying yong sheng tai xue bao = The journal of applied ecology*, 15(4), 646–650.

Rice, D., & Paddy, F. (2015). Effect of Field Drainage on Root Lodging Tolerance in Direct-Sown Rice in Flooded Paddy Field Effect of Field Drainage on Root Lodging Tolerance In, *1008*. https://doi.org/10.1626/pps.6.255

22

Kadam, N., Yin, X., Bindraban, P., Struik, P., & Jagadish, K. (2015). Does morphological and anatomical plasticity during the vegetative stage make wheat more tolerant of water-deficit stress than rice? *Plant Physiology*. Retrieved from http://www.plantphysiol.org/content/early/2015/01/22/pp.114.253328.abstract

Pires, L. F., Cooper, M., Cássaro, F. A. M., Reichardt, K., Bacchi, O. O. S., & Dias, N. M. P. (2008). Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. *CATENA*, 72(2), 297–304. https://doi.org/10.1016/J.CATENA.2007.06.003

Kriesemer, S. K. (2013). Rice cropping systems and resource efficiency, 41. Retrieved from https://www.giz.de/fachexpertise/downloads/giz2013-en-study-rice-cropping-sys-low-res.pdf

Tripathi, R. P., Sharma, P., & Singh, S. (2005). Tilth index: an approach to optimize tillage in rice–wheat system. *Soil and Tillage Research, 80*(1), 125–137. https://doi.org/https://doi.org/10.1016/j.still.2004.03.004

Mondal, S., Kumar, S., Haris, A. A., Dwivedi, S. K., Bhatt, B. P., & Mishra, J. S. (2016). Effect of different rice establishment methods on soil physical properties in drought-prone, rainfed lowlands of Bihar, India. *Soil Research, 54*(8), 997–1006. Retrieved from https://doi.org/10.1071/SR15346

(IRRI) International Rice Research Institute, Los Baños, Philippines. (1985). Soil Physics and Rice, pp. 217-234. https://doi.org/10.1017/S001447970000123X

Song Chen, Xi Zheng, Dangying Wang, Liping Chen, Chunmei Xu, and Xiufu Zhang, (2012). "Effect of Long-Term Paddy-Upland Yearly Rotations on Rice (Oryza sativa) Yield, Soil Properties, and Bacteria Community Diversity," *The Scientific World Journal*, vol. 2012, Article ID 279641, 11 pages, 2012. https://doi.org/10.1100/2012/279641.

Zhou, W., Lv, T. F., Chen, Y., Westby, A. P., & Ren, W. J. (2014). Soil physicochemical and biological properties of paddy-upland rotation: A review. *Scientific World Journal*, 2014. https://doi.org/10.1155/2014/856352

Linh, T. B., Sleutel, S., Vo Thi, G., Le Van, K., & Cornelis, W. M. (2015). Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture. *Soil and Tillage Research*, 154, 44–52. https://doi.org/https://doi.org/10.1016/j.still.2015.06.011

Farooq, M., & Nawaz, A. (2014). Weed dynamics and productivity of wheat in conventional and conservation rice-based cropping systems. *Soil and Tillage Research*,

141, 1–9. https://doi.org/https://doi.org/10.1016/j.still.2014.03.012

Yang, C., Yang, L., & Ouyang, Z. (2005). Organic carbon and its fractions in paddy soil as affected by different nutrient and water regimes. *Geoderma*, 124(1), 133–142. https://doi.org/https://doi.org/10.1016/j.geoderma.2004.04.008

[23]

Djaman, K., Mel, V., Diop, L., Sow, A., El-Namaky, R., Manneh, B., … Irmak, S. (2018). Effects of alternatewetting and drying irrigation regime and nitrogen fertilizer on yield and nitrogen use efficiency of irrigated rice in the Sahel. *Water (Switzerland)*.

Liu, L., Chen, T., Wang, Z., Zhang, H., Yang, J., & Zhang, J. (2013). Combination of site-specific nitrogen management and alternate wetting and drying irrigation increases grain yield and nitrogen and water use efficiency in super rice. *Field Crops Research, 154*, 226-235.

Norton, G., Shafaei, M., Travis, A., Deacon, C., Danku, J., Pond, D., . . . Price, A. (2017). Impact of alternate wetting and drying on rice physiology, grain production, and grain quality. *Field Crops Research*.

[24]

Miro, B., & Ismail, A. (2013). Tolerance of anaerobic conditions caused by flooding during germination and early growth in rice (Oryza sativa L.). F*rontiers in plant science, 4, 269*.

Bajpai, R. K., & Tripathi, R. P. (2000). Evaluation of non-puddling under shallow water tables and alternative tillage methods on soil and crop parameters in a rice ± wheat system in Uttar Pradesh, 55.

Goitom, B. , Tripathi, R. , Ogbazghi, W. and Weldeslassie, T. (2016) Effect of Puddling and Compaction on Water Requirements of Rice at Hamelmalo, Eritrea. Computational Water, Energy, and Environmental Engineering, 5, 27-37. doi: 10.4236/cweee.2016.52003

[25]

Sądej, W., Żołnowski, A. C., & Marczuk, O. (2016). Content of phenolic compounds in soils originating from two long-term fertilization experiments. *Archives of Environmental Protection*, 42(4), 104–113. https://doi.org/https://doi.org/10.1515/aep-2016-0047

Ponnamperuma, F. N. (1984). Straw as source of nutrients for wetland rice. In Organic matter and rice, pp.117-135. International Rice Research Institute, Los Baños, Philippines.

Witt, C., Cassman, K.G., Olk, D.C., Biker, U., Liboon, S.P., Samson, M.I., Ottow, J.C.G. (2000). Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil* 225: 263–278

Barna, G., & Tóth, T. (2017). Soil salinity management in agriculture: Technological advances and applications (Innovations in biological engineering),: edited by S. K. Gupta and Megh R. Goyal, Waretown, NJ: Apple Academic Press, 2017, 454 pp.,. ISBN 978-1-77188-443-3 and 978-1-315-36599-2. *Arid Land Research and Management* (Vol. 31). https://doi.org/10.1080/15324982.2017.1375047

[26]

Yang, C., Yang, L., Yan, T., & Ouyang, Z. (2004). [Effects of nutrient and water regimes on lodging resistance of rice]. *Ying yong sheng tai xue bao = The journal of applied ecology*, 15(4), 646–650.

Tan, X., Shao, D., Liu, H., Yang, F., Xiao, C., & Yang, H. (2012). Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. Paddy and Water Environment, 11, 381-395.

Tuyogon, D. S. J., Impa, S. M., Castillo, O. B., Larazo, W., & Johnson-Beebout, S. E. (2016). Enriching Rice Grain Zinc through Zinc Fertilization and Water Management. *Soil Science Society of America Journal*, 80, 121–134. https://doi.org/10.2136/sssaj2015.07.0262

Mote, K., Velchala, P., Ramulu, V., Avil Kumar, K., & Uma Devi, M. (2018). *Standardization of alternate wetting and drying (AWD) method of water management in low land rice (Oryza sativa (L.))*.

Sun, Y., Ma, J., Sun, Y., Xu, H., Yang, Z., Liu, S., … Zheng, H. (2012). The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China. *Field Crops Research* (Vol. 127). https://doi.org/10.1016/j.fcr.2011.11.015

Zhi, M. (2000). Water efficient irrigation and environmentally sustainable irrigated rice production in China, 1–15.

Uphoff, N. (2006). International Dialogue on Rice and Water: Exploring Options for Food Security and Sustainable Environments, held at IRRI, Los Banos, Philippines. 1–25.

Froes de Borja Reis, A., Estevam Munhoz de Almeida, R., Cocco Lago, B., Trivelin, P. C., Linquist, B., & Favarin, J. L. (2018). Aerobic rice system improves water productivity, nitrogen recovery and crop performance in Brazilian weathered lowland soil. *Field Crops Research*, 218, 59–68. https://doi.org/https://doi.org/10.1016/j.fcr.2018.01.002

Naing, N. S., Soe, Y. M., Thein, S. S., & Moe, K. (2017). Response to yield, water and nitrogen use of hybrid rice under alternate wetting and drying irrigation and controlled release nitrogen fertilizers. *Journal of Agricultural Research*, 4(1), 65–73.

27

Sądej, W., Żołnowski, A. C., & Marczuk, O. (2016). Content of phenolic compounds in soils originating from two long-term fertilization experiments. *Archives of Environmental Protection*, 42(4), 104–113. https://doi.org/https://doi.org/10.1515/aep-2016-0047

Ponnamperuma, F. N. (1984). Straw as source of nutrients for wetland rice. In Organic matter and rice, pp.117-135. International Rice Research Institute, Los Baños, Philippines.

Witt, C., Cassman, K.G., Olk, D.C., Biker, U., Liboon, S.P., Samson, M.I., Ottow, J.C.G. (2000). Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant and Soil 225: 263–278

Shah Moinur Rahman, Ken-ichi Kakuda, Yuka Sasaki and Ho Ando, (2013). Effect of Mid-season Drainage (MSD) on Growth and Yield of Rice in North East Japan. American Journal of Plant Nutrition and Fertilization Technology, 3: 33-42. DOI: 10.3923/ajpnft.2013.33.42

28

Zhao, D., & Kumar, A. (2016). Technical Assistance Consultant ' s Report Regional : Development and Dissemination of Climate-Resilient Rice Varieties for Water-Short Areas of South Asia and Southeast Asia (Financed by the Climate Change Fund and the Government of, (June).

Yushi, Y, Xinqiang, L., Yingxu, C., Jin, L., Jiatao, G., Ru, G. and Liang, L., (2013), Alternate wetting and drying irrigation and controlled release nitrogen fertilizer in late season rice. Effects on dry matter accumulation, yield, water and nitrogen use. Field Crops Res., 144: 212-224.

J. Maheswari, N. Maragatham and G. James Martin, (2007). Relatively Simple Irrigation Scheduling and N Application Enhances the Productivity of Aerobic Rice (Oryza sativa L.). *American Journal of Plant Physiology*, 2: 261-268. DOI: 10.3923/ajpp.2007.261.268

Tan, X., Shao, D., Liu, H., Yang, F., Xiao, C., & Yang, H. (2012). Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. *Paddy and Water Environment*, 11, 381-395.

Mostofa, M. G., Hossain, M. A., Siddiqui, M. N., Fujita, M., & Tran, L.-S. P. (2017). Phenotypical, physiological and biochemical analyses provide insight into selenium-induced phytotoxicity in rice plants. *Chemosphere*, 178, 212–223. https://doi.org/https://doi.org/10.1016/j.chemosphere.2017.03.046

29

Dong, N. M., Brandt, K. K., Sørensen, J., Hung, N. N., Hach, C. Van, Tan, P. S., & Dalsgaard, T. (2012). Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biology and Biochemistry*, 47(August), 166–174. https://doi.org/10.1016/j.soilbio.2011.12.028

30

Malik, R.K. and Yadav, Ashok (2008) Direct seeded rice in the Indo-Gangetic Plain: progress, problem and opportunities. Humphreys, E. and Roth, C-H. (eds). Permanent beds and rice-residue management for ricewheat systems in the Indo-Gangetic Plain Proceedings of a Workshop held in Ludhiana, 7-9Sept 2006 ACI OR Proceedings No. 127, 133-143.

31

Linh, T., Guong, V., Vo Thi Thu, T., le van, K., Olk, D., & Cornelis, W. (2016). *Effects of crop rotation on properties of a Vietnam clay soil under rice-based cropping systems in small-scale farmers' fields* (Vol. 55). https://doi.org/10.1071/SR16123

Yang, C., Yang, L., & Ouyang, Z. (2005). Organic carbon and its fractions in paddy soil as affected by different nutrient and water regimes. *Geoderma*, 124(1), 133–142. https://doi.org/https://doi.org/10.1016/j.geoderma.2004.04.008

32

Gao, H., Chen, X., Wei, J., Zhang, Y., Zhang, L., Chang, J., & Thompson, M. L. (2016). Decomposition Dynamics and Changes in Chemical Composition of Wheat Straw Residue under Anaerobic and Aerobic Conditions. *PLoS ONE*, 11(7), e0158172. https://doi.org/10.1371/journal.pone.0158172

Vallino, M., Fiorilli, V., & Bonfante, p. (2013). Rice flooding negatively impacts root branching and arbuscular mycorrhizal colonization, but not fungal viability. *Plant, Cell & Environment*, 37(3), 557–572. https://doi.org/doi:10.1111/pce.12177

33

Choosai, C., Jouquet, P., Hanboonsong, Y., & Hartmann, C. (2010). Effects of earthworms on soil properties and rice production in the rainfed paddy fields of Northeast Thailand. *Applied Soil Ecology*, 45(3), 298–303. https://doi.org/https://doi.org/10.1016/j.apsoil.2010.05.006

Anas, I., P. Rupela, O., Thiyagarajan, T. M., & Uphoff, N. (2011). A review of studies on SRI effects on beneficial organisms in rice soil rhizospheres. *Paddy and Water Environment - PADDY WATER ENVIRON* (Vol. 9). https://doi.org/10.1007/s10333-011-0260-8

34

Van Dung, T., Ngoc Diep, C., & Springael, D. (2016). Diversity Of The Bacterial Community In Rice Straw Residues In Soil Undergoing Rice-Monoculture Versus Crop Rotation Systems In The Mekong Delta Of Vietnam. *109 World Journal Of Pharmacy And Pharmaceutical Sciences Sjif Impact Factor 6*, 5(10), 109-123.

35

Roger, P. A., & Joulian, C. (1997). Environmental impacts of wetland rice cultivation. *Rice Quality: A Pluridisciplinary Approach*, 23.

Richards, E. E., Masuoka, P., Brett-Major, D., Smith, M., Klein, T. A., Kim, H. C., … Grieco, J. (2010). The relationship between mosquito abundance and rice field density in the Republic of Korea. *International Journal of Health Geographics*, 9, 32. https://doi.org/10.1186/1476-072X-9-32

Singh, S., Shiva, & Singh, S. (2017). Prevalence of occupational skin diseases among rice field workers in Haryana. *International Journal of Community Medicine and Public Health* (Vol. 4). https://doi.org/10.18203/2394-6040.ijcmph20171316

Keiser, J., Maltese, M. F., Erlanger, T. E., Bos, R., Tanner, M., Singer, B. H., & Utzinger, J. (2005). Effect of irrigated rice agriculture on Japanese encephalitis, including challenges and opportunities for integrated

vector management. *Acta Tropica*, 95(1), 40–57. https://doi.org/10.1016/j.actatropica.2005.04.012

36

Van der Hoek, W., Sakthivadivel, R., Renshaw, M., Silver, J. B., Birley, M. H., & Konradsen, F. (2001). Alternate *Wet/Dry Irrigation in Rice Cultivation: A Practical Way to Save Water and Control Malaria and Japanese Encephalitis? Research Report 47, IWMI*. https://doi.org/http://dx.doi.org/10.3910/2009.053

Aplican sistema de riego por secas intermitentes en cultivos de arroz para evitar malaria | *RPP Noticias*. (n.d.). Retrieved from https://rpp.pe/peru/lambayeque/aplican-sistema-de-riego-por-secas-intermitentes-en-cultivos-de-arroz-para-evitar-malaria-noticia-1115802

Keiser, J., Utzinger, J., & Singer, B. (n.d.). *The potential of intermittent irrigation for increasing rice yields, lowering water consumption, reducing methane emissions. and controlling malaria in african rice fields.*

37

Nakandalage, N., Nicolas, M., Norton, R. M., Hirotsu, N., Milham, P. J., & Seneweera, S. (2016). Improving Rice Zinc Biofortification Success Rates Through Genetic and Crop Management Approaches in a Changing Environment. *Frontiers in Plant Science*, 7, 764. https://doi.org/10.3389/fpls.2016.00764

Wang, Y., Wei, Y., Dong, L., Lu, L., Feng, Y., Zhang, J., … Yang, X. (2014). Improved yield and Zn accumulation for rice grain by Zn fertilization and optimized water management. *Journal of Zhejiang University SCIENCE B, 15*(4), 365–374. https://doi.org/10.1631/jzus.B1300263

Roohani, N., Hurrell, R., Kelishadi, R., & Schulin, R. (2013). Zinc and its importance for human health: An integrative review. *Journal of Research in Medical Sciences : The Official Journal of Isfahan University of Medical Sciences, 18*(2), 144–157. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3724376/

38

Duxbury, J. M., & Panaullah, G. (2007). Remediation of Arsenic for griculture Sustainability, Food Security and Health in Bangladesh, 105–110.

Zhu, Y. G., Williams, P. N., & Meharg, A. A. (2008). Exposure to inorganic arsenic from rice: A global health issue? *Environmental Pollution*, 154(2), 169–171. https://doi.org/10.1016/j.envpol.2008.03.015

39

Rejesus, R. M., Martin, A. M., & Gypmantasiri, P. (2013). *Meta-impact assessment of the irrigated rice research consortium.*

Moreno-Jiménez, E., Esteban, E., & Peñalosa, J. M. (2012). The Fate of Arsenic in Soil-Plant Systems BT - Reviews of Environmental Contamination and Toxicology. In D. M. Whitacre (Ed.) (pp. 1–37). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4614-1463-6_1

Wang, X., Ye, Z., Li, B., Huang, L.-N., Meng, M., Shi, J., & Jiang, G. (2014). Growing Rice Aerobically Markedly Decreases Mercury Accumulation by Reducing Both Hg Bioavailability and the Production of MeHg. *Environmental science & technology* (Vol. 48). https://doi.org/10.1021/es4038929

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., da Rosa, E.F.F., van Kessel, C., (2015). Reducing greenhouse gas emissions water use, and grain arsenic levels in rice systems. *Global Change Biology 21*: 407–417;

Carrijo, D. R., Akbar, N., Reis, A. F. B., Li, C., Gaudin, A. C. M., Parikh, S. J., … Linquist, B. A. (2018). Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Research*, *222*, 101–110. https://doi.org/https://doi.org/10.1016/j.fcr.2018.02.026

40

Norton, G. J., Shafaei, M., Travis, A. J., Deacon, C. M., Danku, J., Pond, D., … Price, A. H. (2017). Impact of alternate wetting and drying on rice physiology, grain production,

and grain quality. *Field Crops Research*, 205, 1–13. https://doi.org/https://doi.org/10.1016/j.fcr.2017.01.016

41

Sharma, A., & Nagpal, A. (2017). *Soil amendments: a tool to reduce heavy metal uptake in crops for production of safe food. Reviews in Environmental Science and Bio/Technology*. https://doi.org/10.1007/s11157-017-9451-0

Zhao, K., fu, W., Ye, Z., & Zhang, C. (2015). Contamination and Spatial Variation of Heavy Metals in the Soil-Rice System in Nanxun County, Southeastern China. *International journal of environmental research and public health* (Vol. 12). https://doi.org/10.3390/ijerph120201577

Ghorbani, H. (2008). International Meeting on Soil Fertility Land Management and Agroclimatology. Turkey, 2008. p: 987-996. *International Meeting on Soil Fertility Land Management and Agroclimatology*, 987–996.

Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F., & Zhang, G. P. (2010). *The Influence of pH and Organic Matter Content in Paddy Soil on Heavy Metal Availability and Their Uptake by Rice Plants. Environmental pollution (Barking, Essex : 1987)* (Vol. 159). https://doi.org/10.1016/j.envpol.2010.09.019

42

W. Hundertmark a and T. Facon. Options for effective rice water management - Water Resources, Development and Management Service and Water Management Officer, Regional Office for Asia and the Pacific, FAO, Bangkok, Thailand. Retrieved from: http://www.fao.org/docrep/006/y4751e/y4751e0j.htm

43

Martini, L. F. D., Mezzomo, R. F., Avila, L. A. de, Massey, J. H., Marchesan, E., Zanella, R., … Marques, M. (2013). Imazethapyr and imazapic runoff under continuous and intermittent irrigation of paddy rice. *Agricultural Water Management*, 125, 26–34. https://doi.org/https://doi.org/10.1016/j.agwat.2013.04.005

Schroll, R., Heinrich Becher, H., Dörfler, U., Gayler, S., Grundmann, S., Peter Hartmann, H., & Ruoss, J. (2006). *Quantifying the Effect of Soil Moisture on the Aerobic Microbial Mineralization of Selected Pesticides in Different Soils. Environmental science & technology* (Vol. 40). https://doi.org/10.1021/es052205j

Rejesus, R. M., Martin, A. M., & Gypmantasiri, P. (2013). *Meta-impact assessment of the irrigated rice research consortium*.

Guerra, L. C.; Bhuiyan, S. I.; Tuong, T. P.; Barker, R. (1998). Producing more rice with less water from irrigated systems. Colombo, Sri Lanka: International Water Management Institute (IWMI). v, 24p. (SWIM paper 5) doi: http://dx.doi.org/10.3910/2009.370 Choi, J., Kim, G., P, W., Shin, M., Choi, Y., Lee, S., Lee, D. and Yun, D., (2015). Effect of SRI methods on Water use, NPS pollution discharge, and GHG emission in Korean trials. *Paddy Water Environment*, 13, pp. 205-213.

Ye, Y., Liang, X., Chen, Y., Gu, J. and Li, L., (2013). Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice - Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crops Research*, 144, pp. 212-224

Yang, S., Peng, S., Xu, J., Hou, H. and Gao, X., (2013). Nitrogen loss from paddy field with different water and nitrogen managements in Taihu Lake region of China. *Communications in Soil Science and Plant Analysis*, 44, pp. 2393-2407.

Bigornia, J. S. R., Sparks, A. H., & Sander, B. O. (n.d.). Impact of alternate wetting and drying (AWD) on rice pest and the environment. *Philippine Journal of Crop Science* (Philippines).

Choudhury, A., Kennedy, I., F Ahmed, M., & L Kecskés, M. (2007). Phosphorus Fertilization for Rice and Control of Environmental Pollution Problems. *Pakistan journal of biological sciences: PJBS* (Vol. 10). https://doi.org/10.3923/pjbs.2007.2098.2105

44

Liang, X.Q., Chen, Y.X., Nie, Z.Y. et al. Mitigation of nutrient losses via surface runoff from rice cropping systems with alternate wetting and drying irrigation and site-specific nutrient management practices. Environ Sci Pollut Res (2013) 20: 6980. https://doi.org/10.1007/s11356-012-1391-1

45

Florent, T., Boulakia, S. (2017). Climate Smart Rice Cropping systems in Vietnam. State of knowledge and prospects. Montpellier: CIRAD, 41 p. Retreived from http://agritrop.cirad.fr/586964/1/2017-06+CS+rice+Vietnam+final.pdf

J.K. Ladha, Virender Kumar, P. Chandna, M. Gathala, S. Sharma, H. Pathak, M.M. Alam, R.P. Regmi, U.P. Singh, M. Hafiz, O. Erenstein and V. Balasubramanian. (2009). Integrating crop and resource management technologies for enhanced productivity, profitability and sustainability of the rice-wheat system in South Asia

Chakraborty, D., Ladha, J. K., Rana, D. S., Jat, M. L., Gathala, M. K., Yadav, S., … Raman, A. (2017). Aglobal analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports*, 7, 9342. https://doi.org/10.1038/s41598-017-09742-9

46

United Nations (2004). Global International Waters Assessment. https://pdfs.semanticscholar.org/8025/ac8fa8a4b85652db9 bd89795633c11db5478.pdf

47

Tan, X., Shao, D., Liu, H., Yang, F., Xiao, C., & Yang, H. (2012). Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. *Paddy and Water Environment*, 11, 381-395.

48

Organic Matter and Rice - Google Books. (n.d.). Retrieved from https://books.google.com.ph/s?id=7eCN_04o2uEC&pg=PA606&lpg=PA606&dq=rice+straw+incorporation+planting+labor&source=bl&ots=dDVuOi5XUI&sig=snHFKqVHZjUxPxysya8hK7DZNcE&hl=en-TAAegQICRAB#v=onepage&q=rice%20st

49

Dobermann, A., & Fairhurst, T. (2002). Rice Straw Management. International Plant Nutrition Institute.

50

Hussain, Shahe Alam, M., Kabir, H., K. Khan, A., & M. M. Islam, S. (2009). Water saving Irrigation in rice cultivation with particular reference to alternate wetting and drying method: an overview. *The Agriculturists*, 1, 128-136.

Alam, M. S., Islam, M., Salam, M., & Islam, M. (2009). Economics of Alternate Wetting and Drying Method of Irrigation: Evidences from Farm Level Study. *The Agriculturists*, 7(1), 82. http://doi.org/10.3329/agric.v7i1.5258

Belova, A., Salas, W., Narayan, T., Trump, M., & Westphal, M. (2015). *Vietnam Data Collection to Support LEDs for the Agriculture Sector*. Washington DC.

Bouman, B. A. M., & Tuong, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, 49(1), 11–30. http://doi.org/10.1016/S0378-3774(00)00128-1

Nargis, F., Miah, T. H., Khanam, T. S., & Sarwer, R. H. (2009). Profitability of mv boro rice production under shallow tubewell irrigation system in some selected areas of tangail district. *Progress. Agric.*, 20(1&2), 237–244.

Quicho, E. (2013). *Evaluation of the Adoption and Economic Impacts of Alternate Wetting and Drying Technology in Irrigated Rice-Growing Areas in An Giang Province in the Mekong Delta, Southern Vietnam*. The University of the Philippines in Los Banos.

51

Madramootoo, C. A. (2011). *Water Management for Global Food Security Editor*. Retrieved from: https://www.mcgill.ca/globalfoodsecurity/files/globalfoodsecurity/water_management_for_global_food_security.pdf

52

Tesfai, M., Borrell, A., & Sekhar Nagothu, U. (n.d.). *Climate-smart rice cultivation system to mitigate climate change impacts in India Increased photosynthetic capacity in sorghum View project Sorghum Project (PEARL) View project*.

Tripathi, B., Mahato, R., Yadaw, R., Sah, S., & Adhikari, B. (2012). Adapting Rice Technologies to Climate Change. *Hydro Nepal: Journal of Water, Energy and Environment, 11*(1).

53

Rejesus, R. M., Martin, A. M., & Gypmantasiri, P. (2013). *Meta-impact assessment of the irrigated rice research consortium*.

Gallina, A., & Farnworth, C. R. (2016). Gender dynamics in rice-farming households in Vietnam: A literature review, (183). Retrieved from www.ccafs.cgiar.org

International Rice Research Institute (2016). ADB Technical Assistance Consultant' s Report. "Regional: Development and Dissemination of Climate-Resilient Rice Varieties for Water-Short Areas of South Asia and Southeast Asia". Retrieved from: https://www.adb.org/projects/documents/development-dissemination-climate-resilient-rice-varieties-water-short-areas-south-southeast-asia-tar

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