Growth of rice, PSB Rc 82, and status of nutrients in lowland Agusan soil under alternate wetting and drying and minus-one-element conditions

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Very poor drainage and nutrient deficiencies in soils are major constraints in improving rice growth and yields in lowland areas of Agusan. Alternate wetting and drying (AWD) – a technology that can improve soil chemical properties, and enhance rice growth and yield – is already included in the standard water management for rice production in the irrigated lowland ecosystem of the Philippines. However, for the technology to be considered in integrated crop management for Agusan, it should first be tested under local conditions. Hence, this study compared growth, chlorophyll levels, and biomass of PSB Rc 82 under AWD versus those under continuous submergence (CS). It also determined status of soil nutrients under AWD and CS. Water and fertilizer management for Agusan soil was then recommended. Agusan soil was collected from Remedios T. Romualdez, Agusan del Norte; brought to screenhouse, and used as medium to grow PSB Rc 82 for 59 days after transplanting (DAT). Minus-one-element (MOET) treatments that were subjected to AWD and CS were evaluated: no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), -phosphorus (-P), -potassium (-K), -sulfur (-S), -copper (-Cu), and -zinc (-Zn). Each treatment combination was replicated five times. Growth parameters and chlorophyll levels were recorded weekly until harvesting while biomass was determined after harvesting. Results showed that rice under AWD produced more tillers, more shoot and shoot+root biomass, and less unhealthy leaf biomass compared to rice exposed to CS. However, AWD rice had lower chlorophyll levels, and less shoot and root+shoot biomass in NF and -N treatments. Compared to CS, status of soil nutrients in AWD was less for N; higher for P, K, S, Zn and Cu. Status of N and K were strongly deficient under AWD and CS; Zn almost reached the deficient level in CS. Lower growth, biomass, chlorophyll levels, and N status under AWD can be due to N losses through volatilization and nitrification-denitrification. Higher growth and biomass in CF, -P, -K, -S, -Zn, and -Cu treatments, and the improved status of these omitted nutrients under AWD can be due to various mechanisms induced by the soil's higher reduction-oxidation (redox) potential and pH; such mechanisms eventually enhanced the uptakes of these nutrients. The study implies that, compared to CS, AWD on Agusan soil improves growth and biomass accumulation of lowland rice PSB Rc 82. As such, if water table can be controlled, the following are recommended at 5 t/ha target yield: employment of AWD along with applications of 28-28-43-24 kg/ha N-P-K-S in early stage, 15 kg/ha K in early panicle initiation, and succeeding N additions based on leaf color chart (LCC) readings. The same nutrient applications are recommended if water level is uncontrollably high, but seedlings should be dipped in 2% Zn oxide solution before transplanting. More K fertilizer can be applied if rice, particularly those under CS, exhibit K deficiency.

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INTRODUCTION

Lowland rice soils in Agusan are considered fertile due to their ideal soil pH at 6.7-7.7, high total N at 0.20 - 0.36% (Katyal and Ponnamperuma 1974), and high organic matter contents at 3.2-7.7% (Mabayag et al. 2004a, Katyal and Ponnamperuma 1974, Nemeňo and Siclay 2010). Agusan soils are also high in Olsen available P levels at 15-42 mg/kg (Katyal and Ponnamperuma 1974); high in exchangeable calcium (Ca) and magnesium (Mg) concentrations at 19.4 and 17.0 $cmol_c$/kg, respectively (Nemeňo and Siclay 2010). However, despite this fertility level, stunted growth of rice plants is observed in poorly drained areas. Grain yield in irrigated areas of Caraga, region where Agusan is, ranged at only 3.3-3.6 t/ha in 2014-2017, the second lowest among 16 regions in the Philippines (PSA 2017). Poor drainage, occurrence of nutrient deficiencies, and inappropriate nutrient management (Mabayag et al. 2004a) are major constraints in improving rice growth and yields in Agusan.

The major poorly drained lowland soil in Agusan is Butuan soil series that developed from older alluvial terraces along many sections of the Agusan River. Butuan loam comprises 74,010 ha in the provinces of Agusan del Norte/Sur (Mojica et al. 1967).

Lowland rice soils in Agusan were deficient in several macronutrients: N (Auxtero et al. 2004), NP, NK, NPK (Paculba and Mabayag 2012; Sobrevilla and Mabayag 2012a), or NKS (Sobrevilla and Mabayag 2012a, Mabayag et al. 2004a). Zinc deficiency was also reported in this area (Katyal and Ponnamperuma 1974, Nemeño and Siclay 2010, Castillo and Mamaril 2012).

Chemical fertilizers were either applied or recommended for application to correct nutrient deficiency in Agusan soil (Mabayag et al. 2015, Nemeño and Siclay 2010, Sobrevilla and Mabayag 2012a,b). For instance, Mabayag et al. (2004a) applied ammonium sulfate (21-0-0-24S) and K to soil with NKS deficiency. Furthermore, it was observed that dipping the roots of rice seedlings in Zn oxide solution before transplanting can correct Zn deficiency (Corton et al. 1999, Mabayag et al. 2015).

Appropriate amounts and timing of fertilizer application were examined (Sobrevilla and Mabayag 2012b, Nemeňo and Siclay 2010), or recommended (Mabayag et al. 2015; Cruz et al. 2004, 2002; Manalo et al. 2005). Optimum fertilizer rates for lowland rice in Agusan range at 60-70 kg N/ha, 14-30 kg P_2O_5/ha, and 60-90 kg K_2O/ha. Applying N fertilizer thrice – early tillering, early panicle initiation, and early booting stages – to increase N-use efficiency could raise yield by 10-15% (Mabayag et al. 2015).

The AWD technology is included in the standard water management for irrigated lowland rice in the Philippines (PhilRice 2010). AWD applies water to the field a few days after ponded water disappears (Rejesus et al. 2011, Liang et al. 2013, Buresh 2015). It is irrigation when water is 15 cm below surface (Rahman and Bulbul 2014, Howell et al. 2015, Bouman 2007, Lampayan et al. 2015, IRRI 2014). This is in contrast to the traditional practice of continuous flooding or submergence (CS) – never letting the ponded water disappear. Since the roots of rice under AWD were initially flooded, they are still adequately supplied with water for a certain period although no ponded water can be observed.

Nutrient status in soil and uptake by plants are not similar for AWD and CS mainly due to differences in redox potential and soil pH. Redox potential of AWD soil is either less negative or more positive (Baker 2009, Tuyogon 2014, Yang et al. 2004). This could prevent or minimize the conversion of ionic nutrients, such as Zn^{2+} and sulfate (SO_4^{2-}), into forms unavailable to plants (Fageria et al. 2011, Kirk 2004, Dobermann and Fairhurst 2000). Higher redox potential in AWD soil also decreases the soil solution levels of some nutrients such as Ca and Mg (Fageria et al. 2011, Dobermann and Fairhurst 2000); this decrease could improve the absorption or uptake of other nutrients such as P, K, Zn and Cu (Norton et al. 2017, Fageria et al. 1995, Fageria 2001, Dobermann and Fairhurst 2000).

Soil pH in AWD soil is higher (Baker 2009, Tuyogon 2014, Yang et al. 2004). This pH level may favor the function of roots, and enhance K uptake (Alam et al. 1999). Moreover, the redox potential and pH under AWD leads to production of less soluble iron (Fe^{2+}) (Fageria et al. 2011, Chen et al. 2008) needed for the oxidation or formation of $Fe(OH)_3$ deposits or Fe plaques on roots of wetland plants (Jiang et al. 2009). Such condition would reduce soil adsorption of some nutrients such as P, Ca, manganese (Mn), Zn and Cu (Chen et al. 2008, Jiang et al. 2009, Zhang et al. 1999, Yang et al. 2014, Zhou et al. 2015) thereby increasing their concentrations in plants (Zhang et al. 1999, Zhang et al. 1998, Greipsson and Crowder 1992, St-Cyr and Campbell 1996, Tripathi et al. 2014).

AWD can positively affect lowland rice. Occasional drying corrects deficiency of micronutrients (Dobermann and Fairhurst 2000), and reduces absorption of toxic substances from the soil (Linquist et al. 2014, Norton et al. 2012, Yang et al. 2009). It enhances leaf photosynthesis and root activity, and increases the number of productive tillers (Yang and Zhang 2010). Rice under alternate wetting and moderate soil drying had better growth (Rahman and Bulbul 2014; Zhang et al. 2010, 2009; Howell et al. 2015; Ye et al. 2013; Zhang et al. 2009; Yang et al. 2009) and grain yield (Zhang et al. 2009, Yang et al. 2009) than rice under CS. However, cycles of submergence and drying result in more N losses through volatilization and nitrification-denitrification (Nguyen et al. 2012; Xu et al. 2013, 2012).

Nutrient limitations have been assessed, and fertilizer management recommendations have been formulated for Agusan soil. Meanwhile, AWD could improve soil chemical characteristics, rice growth, and yield; controlled irrigation is also being promoted to Agusan rice farmers (Auxtero et al. 2003). However, to the authors' knowledge, there is no available information about the effects of AWD on soil nutrient status and rice growth under Agusan conditions. This, despite the fact that such information are vital in coming up with integrated crop management for lowland rice areas in Agusan.

This study compared growth, chlorophyll levels and biomass for AWD versus CS rice. It also contrasted nutrient status for AWD versus CS soil across MOET treatments, and proposed mechanisms that could explain the status. From such information, water and fertilizer management for Agusan soil were recommended.

MATERIALS AND METHODS

1. Medium for Growing Rice

Sufficient amount of soil (Butuan series) was collected from a rice farm in Remedios T. Romualdez, Agusan del Norte (09.06788889°N, 125.58861111°E) after final leveling. Soil was added with irrigation water for puddling, passed through a fine mesh to remove undecomposed plant materials, and mixed

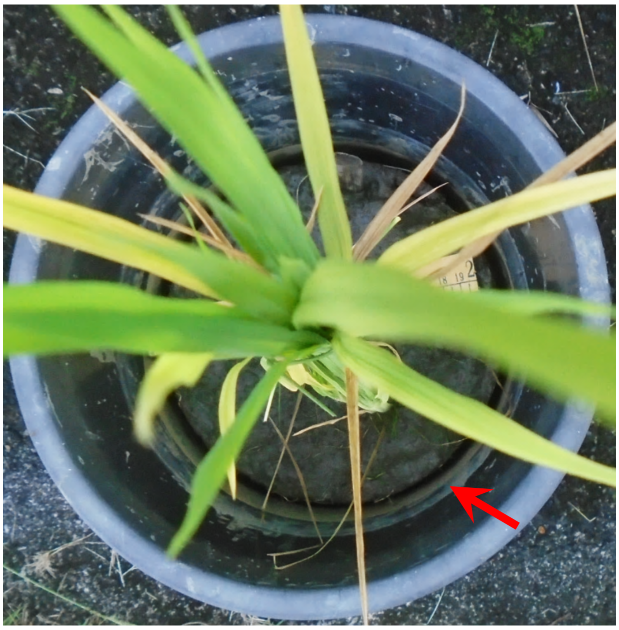

Figure 1: Cracks along the entire periphery of soil under alternate wetting and drying.

thoroughly. The soil had the following characteristics: silt loam texture, pH 6.5, 5.3% organic matter, 0.29% total N, 18 mg/kg Olsen available P, and 0.32 $cmol_c$/kg exchangeable K.

2. Crop Establishment and Maintenance

Under the experiment in a screenhouse of PhilRice Agusan from 11 January until 11 March 2018, four (4) kg of homogenized soil was transferred into plastic pails. Each pail was planted with five 12-day-old seedlings of PSB Rc 82, one of the varieties suitable in the locality (Mabayag et al. 2004b, Nemeňo and Siclay 2010). Each pail was thinned when seedlings were fully established, the two most vigorous of which were retained.

3. Nutrient Omission as Experimental Factor

The experiment had two factors: minus-one element and water management - each combination of which was replicated five times.

MOET is based on the context that the rice plant's growth is a reflection of the essential elements that it extracts from the soil. Its principle is based on Liebeg's law of minimum – level of plant production or yield can be no greater than that allowed by the most limiting essential growth factor.

The method used for conducting the experiment using MOET follows that of Azhiri-Sigari (2003) and Sigari (2003). Four (4) kg of puddled soil was each placed into eight plastic pails to represent NF, CF, -N, -P, -K, -S, -Cu, and -Zn. Rice was grown in the pails until maximum tillering stage.

4. Water Management as Experimental Factor

Two water management treatments were tested: AWD and CS. Initial water level in AWD pails was 3 cm. Soils in the pails were then allowed to dry until cracks appeared along the entire periphery of soil (Figure 1). Two days after such cracking, pails were watered up to the 2-cm mark. Soils in the pails were allowed to dry and crack again, then watered up to the 2 cm mark if no standing water can be observed in the cracks. The drying and wetting processes were repeated until harvesting.

Water levels in CS pails were maintained at 2-3 cm from transplanting until harvesting. Transparent plastics were used as roof of the screenhouse experiment to prevent rainwater from the pails.

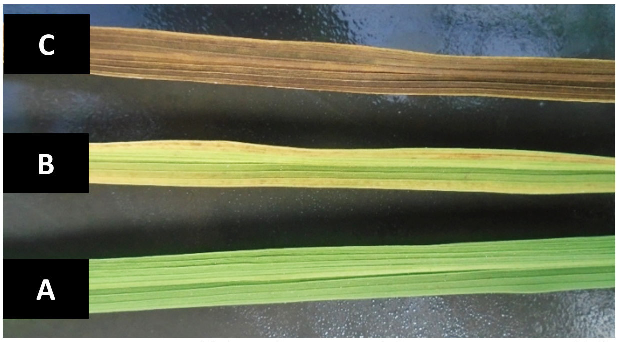

Figure 2: Healthy leaf (A), leaf with dots (B), and withered leaf (C).

5. Measurements of Rice Growth, Chlorophyll Levels, and Biomass

Plant height was measured and tillers were counted weekly from 19 DAT until biomass harvesting. Total numbers of leaves and unhealthy leaves were assessed weekly from 14 until 56 DAT. An unhealthy leaf can either be a leaf with at least 50% of its surface area covered with dots or withered (Figure 2).

Chlorophyll levels of the top most expanded or flag leaf were measured using chlorophyll meter (SPAD 502 plus, Konica Minolta) at 8:00-9:00 AM weekly from 22 until 57 DAT. Quantitative SPAD readings were done at the top, middle, and bottom portions of the leaf. Qualitative measurements using the LCC were done weekly from 14 until 56 DAT.

Shoots and roots were harvested at 59 DAT; unhealthy leaves were separated from the healthy leaves and shoots. Shoots, roots, and leaves were oven-dried until constant weight to determine their oven-dry biomass.

6. Environmental Factors

Data on temperature and relative humidity were recorded daily at 8:00 AM and 2:00 PM using a portable thermometer with dry and wet bulbs. Table 1 shows the average, median, maximum and minimum temperatures, and relative humidities throughout the duration of the experiment.

Table 1: Descriptive statistics for temperature and relative humidity throughout the duration of the experiment†.

Parameter	Mean	Median	Minimum	Maximum
Temperature, °C				
8:00 AM	25.9	26.0	21.5	32.0
2:00 PM	29.2	29.0	21.5	35.0
Relative Humidity, %				
8:00 AM	75.6	74.5	67.0	88.0
2:00 PM	69.6	70.0	56.0	87.0

†data for 1-58 days after transplanting

7. Experimental Design, and Data Analyses, Interpretation and Presentation

The experimental units or pails were arranged into five blocks due to the perceived differences in sunshine duration within the screenhouse. Each block contained all the possible combinations of water management and MOET treatments.

All rice growth, chlorophyll levels, and biomass data were not normally distributed based on the Shapiro-Wilk test. Hence, the Wilcoxon signed ranks test was used to compare all data for AWD versus CS across MOET treatments.

Data on growth and chlorophyll levels of AWD rice were considered higher or lower than CS rice if significantly different for at least one growth stage, or numerically higher or lower in four out of five pairs of AWD-CS rice in most growth stages. Data on tiller count and biomass of AWD rice were considered

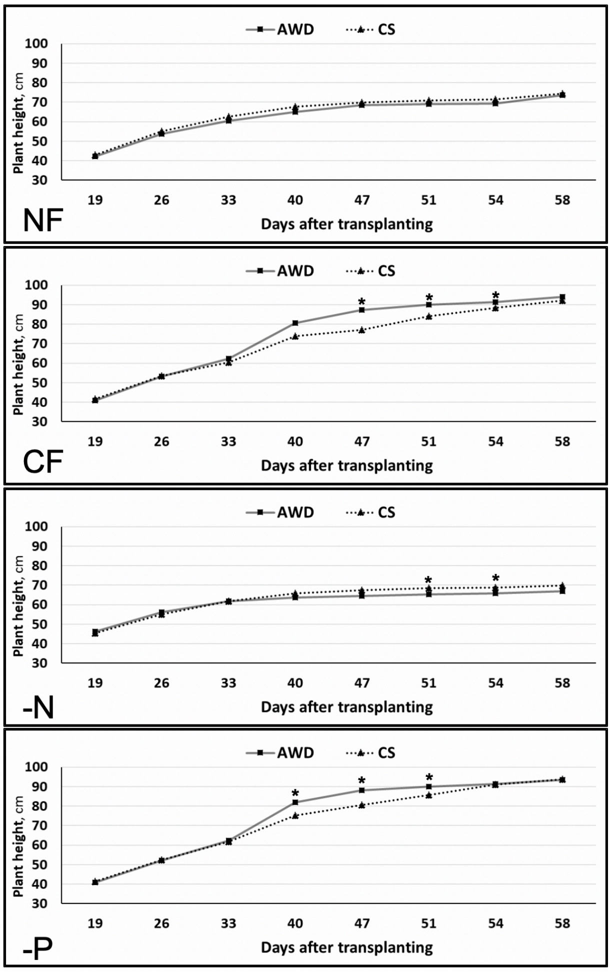

Figure 3A: Comparisons for plant height dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus (-P) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above plant height data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

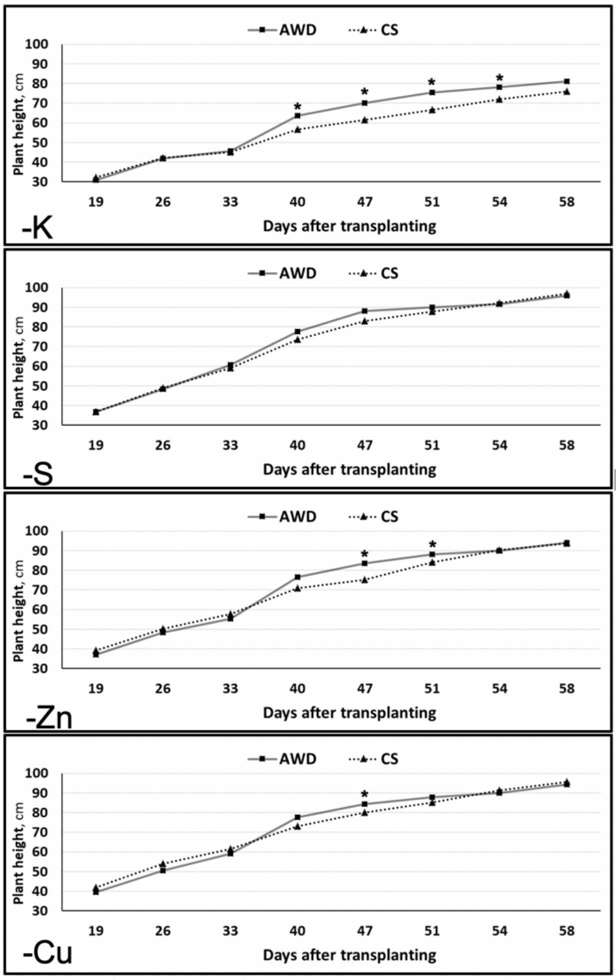

Figure 3B: Comparisons for plant height dynamics of rice under alternate wetting and drying AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), zinc (-Zn), and -copper (-Cu) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above plant height data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

higher or lower than CS rice if significantly different, or numerically higher or lower in four out of five pairs of AWD-CS rice.

Status of nutrients for AWD versus CS across MOET treatments were based on tiller count and biomass at harvest. A nutrient was considered deficient if tiller count or biomass of a corresponding MOET treatment was <80%; sufficient if >80% tiller count or biomass of rice supplied with complete set of nutrients (CF) was seen in either AWD or CS.

Results of data analyses and interpretations are presented in graphs. Mechanisms that could explain the nutrient status are proposed. Water and fertilizer management practices are then recommended based on the results.

RESULTS AND DISCUSSION

1. Comparisons for growth and biomass of rice under alternate wetting and drying (AWD) versus those under continuous submergence (CS) across minus-one-element treatments

Rice under AWD were taller than rice exposed to CS in CF and -K treatments (Figures 3A and B). Rice under AWD, however, were shorter in NF and -N treatments. These results agree with previous reports on AWD versus CS. Leaf elongation rates of AWD rice were significantly greater by 46% (Norton et al. 2017).

Five high-yielding rice varieties exposed to AWD were significantly taller at flowering and physiological maturity stages (Sarker et al. 2017). AWD rice were taller by 2% for two seasons in India (Boruah et al. 2018).

Rice under AWD had more tillers in CF, -P, -S, -Zn and -Cu treatments (Figures 4A and B). Several researches yielded similar findings: AWD rice had significantly higher number of tillers by 16% (Rahman and Bulbul 2014); significantly greater number of tillers from 21 until 56 DAT (Howell et al. 2015); two more tillers at the end of AWD cycles (Norton et al. 2017); significantly higher number of effective tillers (Sarker et al. 2017); 16-18% more effective tillers (Boruah and Das 2018).

The following characteristics were observed in rice exposed to AWD: 1) more leaves in -Zn and -Cu treatments (Figures 5A and B); 2) lower percentage withered leaves in -N, -P, -K and -Cu treatments (Figures 6A and B); and 3) lower percentage leaves with dots in CF, -K, -Zn and -Cu treatments (Figures 7A and B). Similarly, better leaf area index of AWD rice were recorded in the past: significantly higher at panicle initiation, flowering, and physiological maturity stages (Sarker et al. 2017); 19-29% greater in two crop growth stages for two seasons (Boruah et al. 2018).

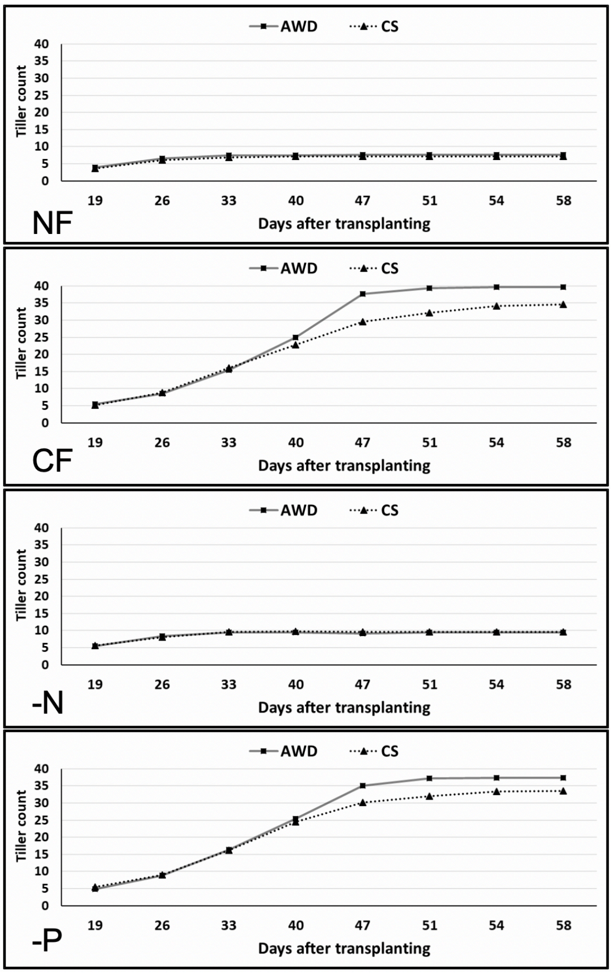

Figure 4A: Comparisons for tiller count dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus (-P) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above tiller count data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

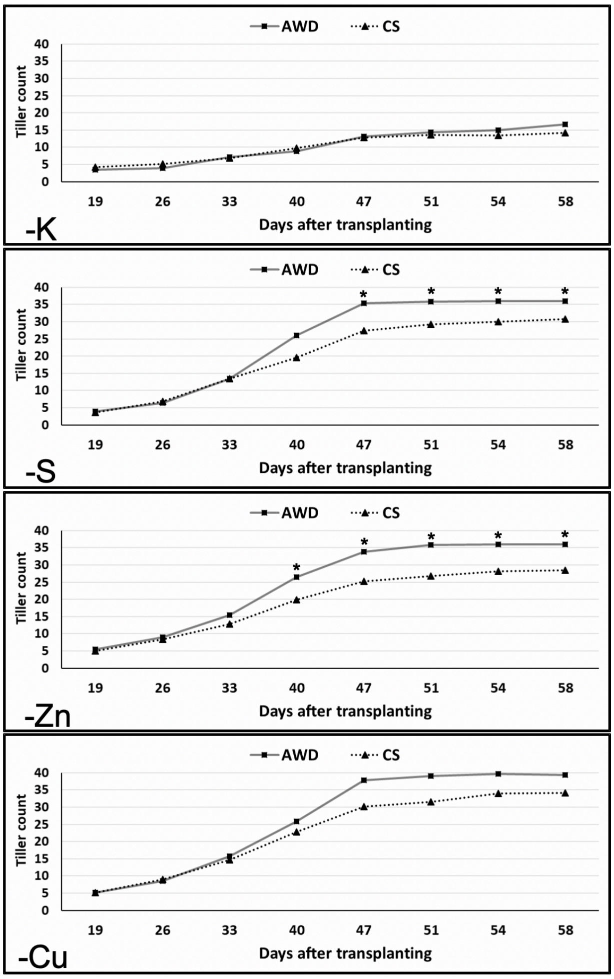

Figure 4B: Comparisons for tiller count dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), zinc (-Zn), and -copper (-Cu) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above tiller count data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

Unhealthy leaf biomass of rice under AWD was lower compared to rice under CS in CF, -N, -P, -K, -Zn and -Cu treatments (Figure 8A). Healthy leaf+stalk, shoot, and shoot+root (total) biomass of rice employed with AWD was higher in CF, -P, -K, -S, -Zn and -Cu treatments; lower in NF and -N treatments (Figure 8B-D). Root biomass of rice exposed to AWD was less in -N, -S and -Zn treatments; more in -K treatment (Figure 8E). Shoot biomass or straw yields of AWD rice were also reported to be either significantly or numerically higher (Howell et al. 2015, Ye et al. 2013, Norton et al. 2017, Sarker et al., 2017, Baker 2009), and to be 3-8% higher than those of CS rice (Rahman and Bulbul 2014, Zhang et al. 2010, Boruah et al. 2018).

The following improvements in AWD rice were found: higher shoot+root biomass (Ye et al. 2013), significantly higher biological yield by 14% (Rahman and Bulbul 2014), significantly or numerically higher crop growth rates in 30-60 and 60-90 DAT for two seasons (Boruah and Das 2018) and in three crop stages (Sarker et al. 2017), and higher root biomass (Ye et al. 2013).

2. Comparisons for chlorophyll levels of rice under AWD versus those under CS across minus-one-element treatments

SPAD readings were lower in plants exposed to AWD in all growth stages of -N treatment, and in most growth stages of NF and CF treatments (Figure 9). LCC readings were also lower in plants under AWD in most growth stages of NF, -N, and -Cu treatments (Figure 10). Previous researches also indicated that AWD rice grown for 3, 5, 7 and 9 weeks exhibited either significantly or numerically lower chlorophyll levels (Khairi et al. 2015a, b), and fluorescence (Khairi et al. 2015a, b) than CS rice.

3. Status of soil nutrients under AWD and CS

Compared to CS, status of soil nutrients in AWD was less for N; higher for P, K, S, Zn and Cu (Figure 11A and B). The same trends were found in past experiments that compared AWD and CS. Soil extracts from root zone of AWD soil, for example, had lower N phytoavailability in the seventh week (Khairi et al. 2015a). Water in AWD soil had less ammonium (NH_4^+) concentrations at tillering, booting, panicle initiation, and grain milking stages (Shao et al 2015).

Availabilities of P (Nhan et al 2015), K (Khairi et al. 2015a), Zn (Tuyogon 2014, Norton et al. 2017, Masunaga and Fong 2018), and Cu (Masunaga and Fong 2018, Tuyogon 2014) in AWD or non-flooded soil were reported to be greater. P (Yang et al. 2004, Norton et al. 2017), K (Yang et al. 2004), Zn (Tuyogon 2014), and Cu levels (Norton et al. 2017, Tuyogon 2014) of rice grown in AWD soil were observed to be higher. P and K uptakes (Boruah et al. 2018, Yang et al. 2004) of rice grown in AWD

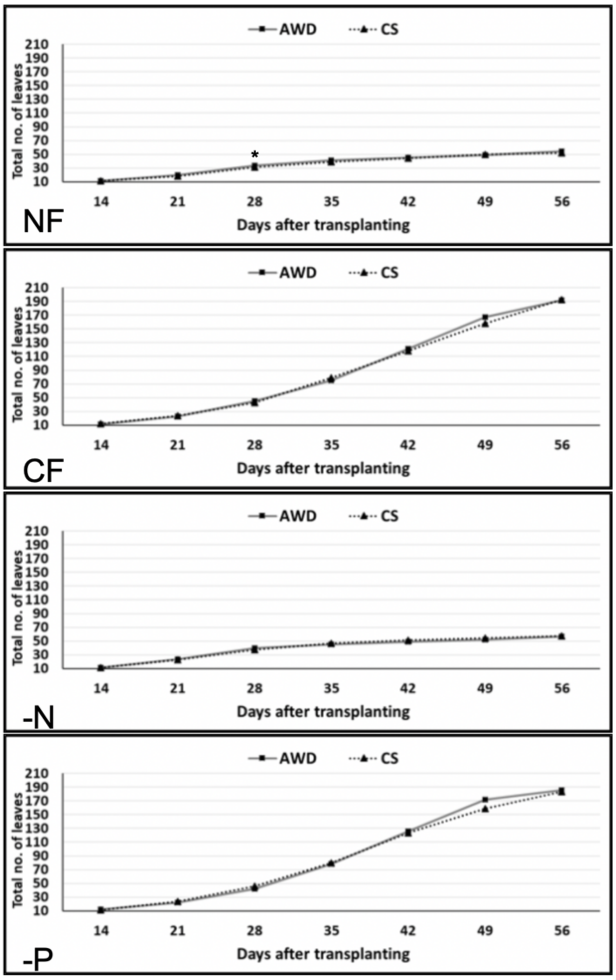

Figure 5A: Comparisons for <u>total leaf no.</u> dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus (-P) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above total leaf no. data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

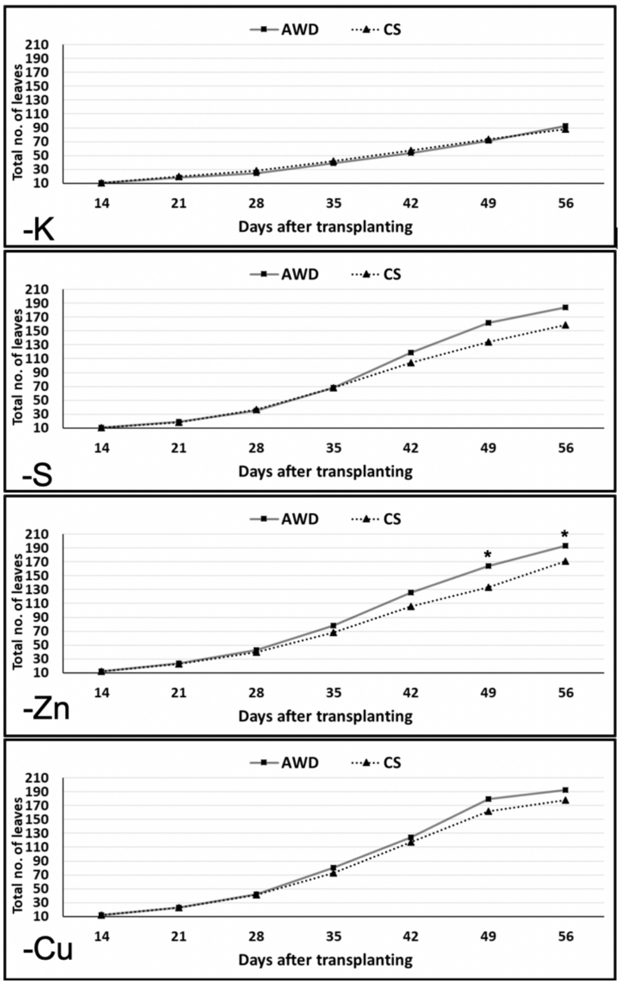

Figure 5B: Comparisons for <u>total leaf no.</u> dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), -zinc (-Zn), and -copper (-Cu) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above total leaf no. data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

soil were found to be greater. N and K were strongly deficient, while P, S, Zn and Cu were sufficient under AWD and CS (Figures 11A and B). Zn was almost deficient in the soil exposed to CS. Deficiencies of N and K (Sobrevilla and Mabayag 2012a, Mabayag et al. 2004a, Paculba and Mabayag 2012, Castillo and Mamaril 2012), and Zn (Katyal and Ponnamperuma 1974; Nemeño and Siclay 2010, Castillo and Mamaril 2012) were also reported in Agusan. Sufficiencies of P (Katyal and Ponnamperuma 1974, JC Magahud unpublished observations), S (JC Magahud, unpublished observations), and Cu (Castillo and Mamaril 2012) were also found in the area.

4. Factors that affect status and uptake of soil nutrients under AWD and CS

Lower growth, biomass, chlorophyll levels, and N status under AWD can be attributed to lower N availability as a consequence of N losses through volatilization and nitrification-denitrification. Volatilization is the conversion of nitrate (NO_3^-) into ammonia (NH_3) gas; nitrification-denitrification is the conversion of NH_4^+ to NO_3^- followed by gaseous loss of nitrogen dioxide (N_2O) or elemental nitrogen (N_2). Compared to CS, AWD soil exhibited 10 (Dong et al. 2012) and 19-21% (Xu et al. 2013) higher volatilization; 6x more nitrification-denitrification (Dong et al. 2012); higher N_2O emissions (Tuyogon 2014) by 1.43-1.90 kg N/ha (Xu et al. 2013). Furthermore, agronomic efficiencies of applied N were reported to be lower in rainfed than in flooded condition (Capistrano and Hayashi 2019). Higher growth and biomass in CF, -P, -K, -S, -Zn, and -Cu treatments, and the improved status of these omitted nutrients under AWD can be due to various mechanisms resulting from the higher redox potential and pH in AWD soil. Such mechanisms – that either increased the available forms of certain nutrients in soil solution or favored the function of roots – eventually led to enhanced uptakes of these nutrients.

Owing to its higher redox potential and pH, lower amounts of Fe^{2+} could be produced and oxidized in the rhizosphere of AWD soil. Less Fe plaques could form on roots exposed to AWD than those under CS; this could lower the adsorption of P, Zn and Cu on roots or in rhizosphere, and enhanced these nutrients' availabilities to plants. The amount of plaques was found to be much lower, per unit root weight, in rice grown under 60 and 100% water-holding capacities than those under submerged condition (Chen et al. 2008).

The following reports indicated that Fe plaques prevent or reduce P, Zn and Cu uptake: (1) positive correlations (r = 0.69-0.98) for quantities of plaques versus P, Zn and Cu levels in plaques (Chen et al. 2008, Jiang et al. 2009, Zhang et al. 1999), and on roots (Jiang et al. 2009, Yang et al. 2014); (2) negative correlations for Cu concentrations in plaques versus roots (Zhou et al. 2015); and lower P, Zn and Cu levels either in rice grown

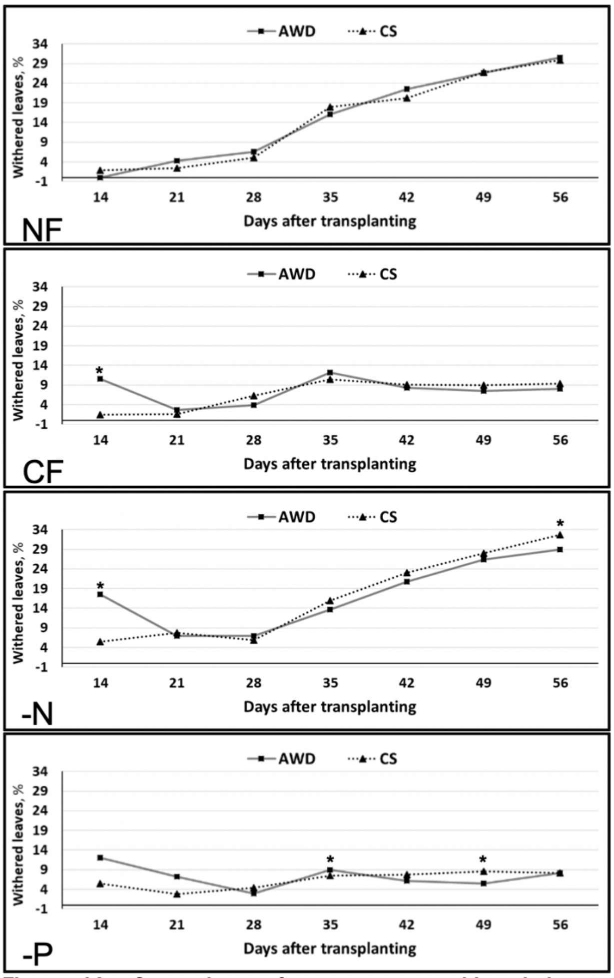

Figure 6A: Comparisons for percentage withered leaves dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above percentage withered leaves data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

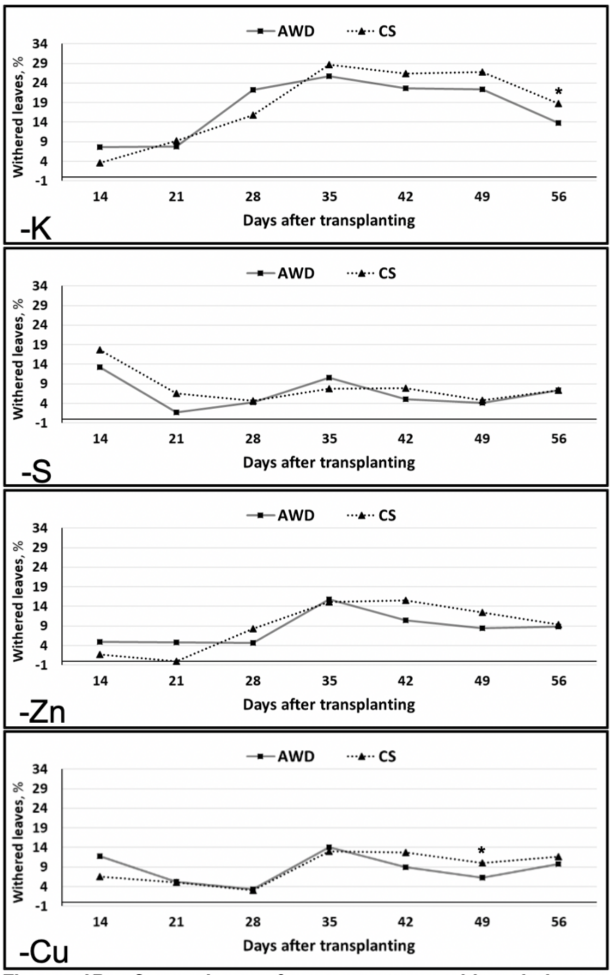

Figure 6B: Comparisons for percentage withered leaves dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), -zinc (-Zn), and -copper (-Cu) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above percentage withered leaves data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

in $Fe(OH)_3$-containing nutrient solution, or in wetland plants with more plaques on roots (Zhang et al. 1999, 1998; Greipsson and Crowder 1992; St-Cyr and Campbell 1996).

Lower Ca and Mg concentrations were possibly present in the AWD soil solution; this decrease in competing cations can improve K absorption. The observed K deficiency (Figure 8) despite the intermediate exchangeable K status of the growth medium, at 0.32 $cmol_c$/kg, can be due to the wide (Ca+Mg): K ratio of Agusan soils. Very high exchangeable Ca and Mg concentrations at 19.4 and 17.0 $cmol_c$/kg, respectively, and medium exchangeable K levels at 0.29 $cmol_c$/kg were also noted in Agusan rice area (Nemeňo and Siclay 2010).

Various studies agree with the proposed effect of Ca and Mg on K. Decreasing K levels were observed in shoots of rice grown in nutrient solutions with increasing Ca concentrations from 0.03 to 0.15 $cmol_c$/kg; in dry bean plants, Ca amounts from 10.0 to 12.3 $cmol_c$/kg. Decreasing K levels were also noted in shoots of rice grown in solutions with increasing Mg concentrations from 0.002 to 0.417 $cmol_c$/kg (Fageria 2001). Soil application of high amounts of Ca and Mg-containing lime at 4 g/kg reduced K uptake in five crop species (Fageria et al. 1995). Compared to CS rice, shoots of AWD rice had 8% lower Ca concentrations; 7% less Mg levels; this coupled by higher K concentrations in AWD than CS shoots. Furthermore, grains of AWD rice had 9% lower Ca amounts; 5% less Mg concentrations (Norton et al. 2017). Lower Ca and Mg levels in AWD soil solution probably enhanced P, Zn and Cu uptakes. Several reports support this concept. For instance, P levels significantly decreased in shoots of rice grown in nutrient solutions with increasing Ca concentrations from 0.01 to 0.15 $cmol_c$/kg; in dry bean plants, Ca amounts from 4.9 to 12.5 $cmol_c$/kg. Zn and Cu uptakes significantly reduced in dry bean plants grown in solutions with increasing Ca concentrations from 4.9 to 12.5 $cmol_c$/kg (Fageria 2001).

Increasing rates of Ca and Mg-containing lime reduced the P, Zn and Cu uptakes, and enhanced Ca and Mg uptakes in five crop species (Fageria et al. 1995). Furthermore, $MgCO_3$ and $CaCO_3$ (Dobermann and Fairhurst 2000) holds and sorbs Zn^{2+}; this sorption was suggested to occur in alkaline soils of Agusan (Katyal and Ponnamperuma 1974).

Soil pH could have been higher in AWD soil; this positively affected the function of roots, and enhanced K absorption. Soil pH levels were also reported to be higher in AWD soil (Baker 2009, Tuyogon 2014, Nhan et al. 2015). K concentrations increased in lowland rice, wheat and soybean with increasing pH levels: 6.4, 6.7 and 7.0 (Fageria and Baligar 1999). The nutrient-

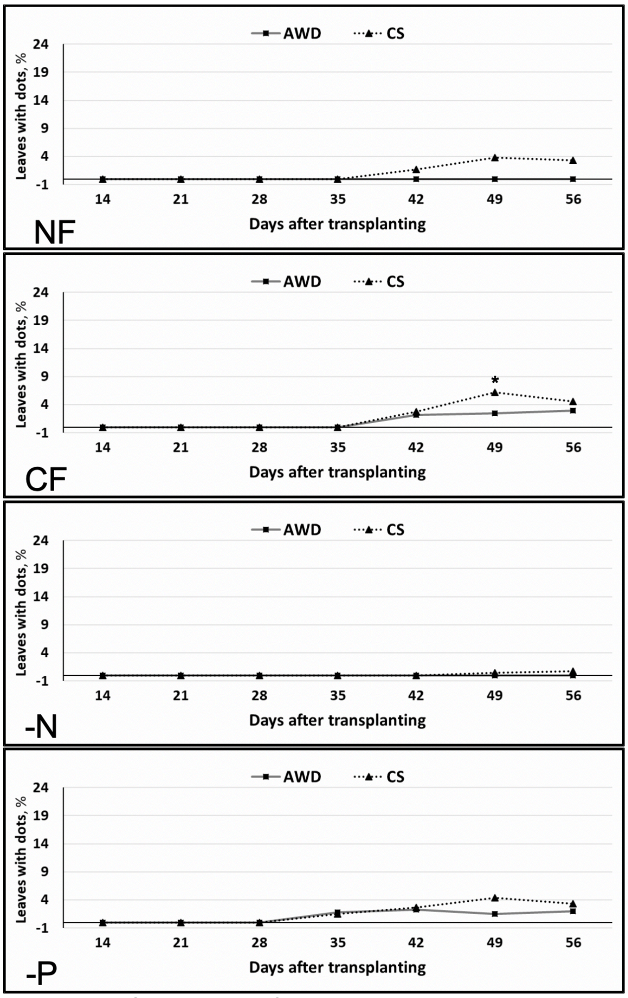

Figure 7A: Comparisons for <u>percentage leaves with dots</u> dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus (-P) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above percentage leaves with dots data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

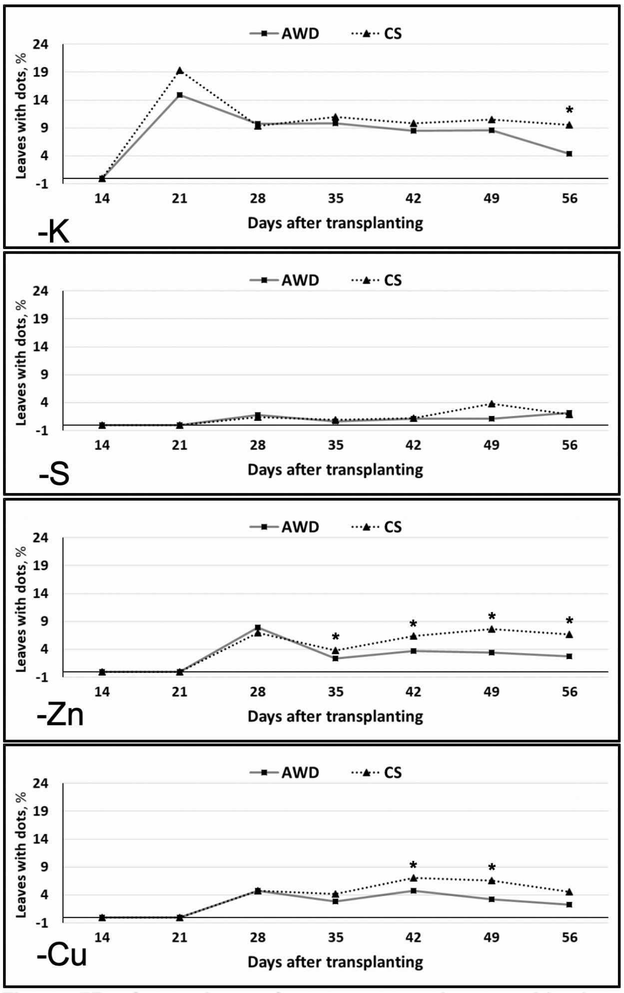

Figure 7B: Comparisons for <u>percentage leaves with dots</u> dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), -zinc (-Zn), and -copper (-Cu) treatments; mean of five replications per water management and minus-one element combination; asterisk (*) above percentage leaves with dots data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 5% significance level.

uptake model of Chen and Barber (1990) accurately predicted the effect of soil pH on K uptake ($Y = 67 + 0.94X$, $r^2 = 0.99$). Moreover, significantly positive correlation for soil pH and rice K levels was noted (Magahud et al. 2015).

The more acidic CS soil, with more solution concentration of hydrogen ion (H^+), can reduce the function of root plasma membrane, and induce K loss or inhibit the nutrient's uptake. This can lead to poor root growth (Alam et al. 1999).

The higher redox potential in AWD soil creates a microbiological environment that favors S availability. In contrast to the flooded soil, higher soil redox potential, less S-reducing and more S-oxiding bacteria were observed in the rhizosphere of AWD rice (Das et al. 2016).

In flooded soils, SO_4^{2-} is reduced to hydrogen sulfide (H_2S) by anaerobic microbial activities. Furthermore, conversion of Fe^{3+} to Fe^{2+} precedes SO_4^{2-} reduction; Fe^{2+} will always be present in the soil solution by the time H_2S is produced, so that H_2S will be converted to insoluble iron sulfide (FeS) (Fageria et al. 2011).

The higher redox potential in AWD soil improved Zn availability. Zn is weakly complexed by the main functional groups in organic matter, but it forms insoluble sulfide (ZnS) under SO_4^{2-}-reducing conditions. Zn tends to be highly immobile under anaerobic conditions, but released in soluble and mobile forms under acid oxidized conditions (Kirk 2004).

5. Physiological factors that affect growth and biomass under AWD and CS

Higher growth and yields in AWD rice can be explained by the variations in phytohormone levels. Higher tiller count and straw yields in AWD rice, for example, were coupled with higher abscissic acid concentrations (Norton et al. 2017). Tiller production was either promoted (Liu et al. 2011) or reduced (Yeh et al. 2015) by cytokinins. Better growth and yield in AWD rice were associated with higher cytokinin (Zhang et al. 2009) and iso-pentenyladenine levels; lower trans-zeatin concentrations (Norton et al. 2017).

Lower root biomass of AWD rice in -S and -Zn treatments (Figure 8) can be due to shoot-to-root partitioning of less photosynthates in these treatment combinations. Soil status (Figure 10) and plant uptakes of S and Zn are presented to be better in AWD than CS. This concept agrees with Thornley Model – nutrient deficiencies favor photosynthate partitioning to the roots (Marschner et al. 1996, Hermans et al. 2006). Past findings also revealed that applications of S (Wang et al. 2003, Gilbert and Robson 1984, Stuiver et al. 2009) would result in

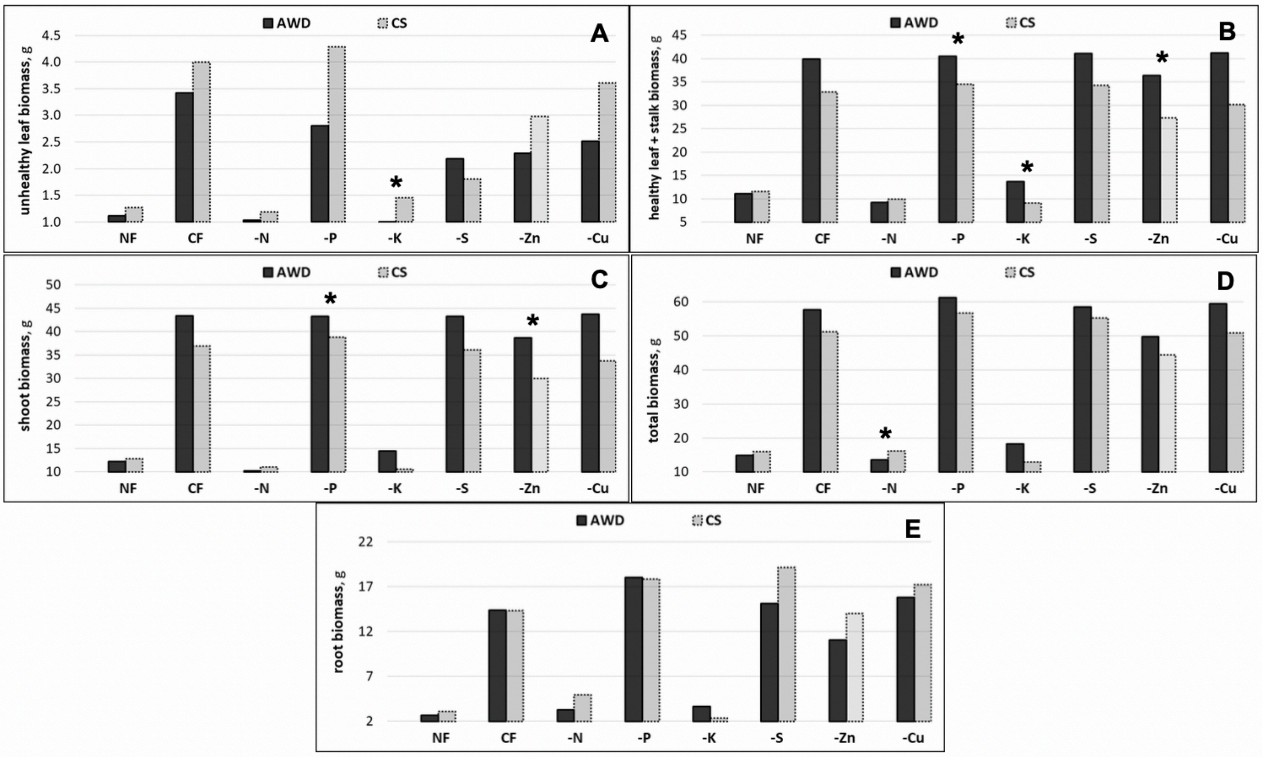

Figure 8: Comparisons for oven-dry weight of unhealthy leaf (A), unhealthy leaf + shoot (B), shoot (C), shoot+root (total) (D), and root (E) biomass of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), -phosphorus (-P), -potassium (-K), -sulfur (-S), zinc (-Zn), and -copper (-Cu); mean of five replications per water management and minus-one element combination; asterisk (*) above biomass data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are significantly higher than CS or vice-versa.

lower root:shoot biomass than non-application or deficiency of this nutrient. Less root biomass of AWD rice in -N treatment, and the lower soil status (Figure 8) and plant uptake of N in this study are contrary to earlier reviews (Marschner et al. 1996, Hermans et al. 2006) and reports (Chun et al. 2005, Cai et al. 2012, Trubat et al. 2006) – deficiencies or zero N would cause higher root:shoot biomass.

Higher root biomass of AWD rice in -K treatment can be due to shoot-to-root partitioning of more photosynthates. Soil status (Figure 8) and plant uptake of K are presented to be better in AWD than CS. It is known that leaves of K-deficient plants accumulate carbohydrate; they are less able to translocate photosynthates to the root via their phloem, and rarely increase their root biomass (Hermans et al. 2006). Previous reports also revealed that sufficiency or higher levels of K resulted in more root:shoot biomass (Cai et al. 2012) and root growth (Jia et al. 2008).

6. Water and fertilizer management for Agusan soil

If water level can be controlled, either due to minimal rainfall or presence of drainage structure, AWD should be employed to improve growth of lowland rice PSB Rc 82. N and K were deficient in soil under AWD (Figure 11); hence, the following are recommended at 5 t/ha target yield: 28-28-43-24 kg/ha N-P-K-S in early stage, and 15 kg/ha K in early panicle initiation; subsequent N applications are based on weekly LCC readings from 21 DAT or 28 days after seeding to early flowering (PhilRice 2010).

The same nutrient applications are recommended if water level is uncontrollably high either due to heavy rains or absence of drainage structure. Aside from N and K, Zn was also deficient in soil exposed to CS (Figure 10); hence, roots of rice seedlings should be dipped in 2% Zn oxide solution before transplanting (Corton et al. 1999, Mabayag et al. 2015), or 9 kg/ha Zn should be topdressed at 14 DAT (PhilRice 2007).

More K fertilizer can be applied if rice, particularly those under CS, exhibit K deficiency.

CONCLUSION AND RECOMMENDATION

Rice exposed to AWD produces more tillers; more healthy leaf+shoot, shoot, and shoot+root biomass; and less unhealthy leaf biomass in CF, -P, -K, -S, -Zn and -Cu treatments than rice under CS. However, AWD results in lower chlorophyll levels, and less shoot and root+shoot biomass in NF and -N treatments.

Compared to CS, status of soil nutrients in AWD was less for N; higher for P, K, S, Zn and Cu. Status of N and K are strongly deficient under AWD and CS; Zn can also reach the deficient level in CS. Lower growth, biomass, chlorophyll levels, and N status under AWD can be due to N losses through volatilization and nitrification-denitrification.

Higher growth and biomass in CF, -P, -K, -S, -Zn, and -Cu treatments, and the improved status of these omitted nutrients under AWD can be due to various mechanisms induced by the higher soil redox potential and pH; such mechanisms eventually enhanced the uptake of these nutrients.

The study implies that, compared to CS, AWD on Agusan soil improves growth and biomass accumulation of lowland rice PSB Rc 82. As such, if water table can be controlled the following are recommended at 5 t/ha target yield: AWD should be employed along with applications of 28-28-43-24 kg/ha N-P-K-

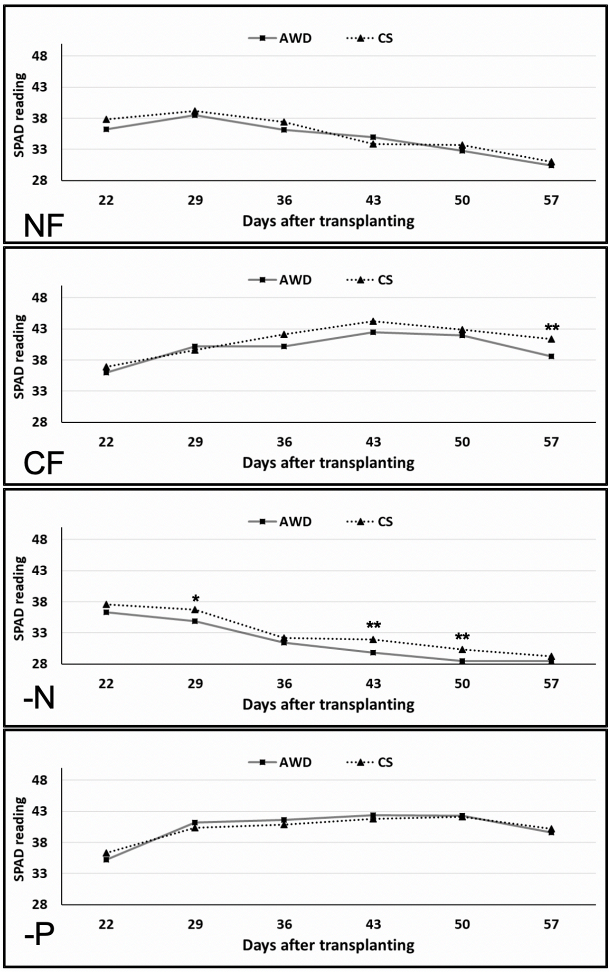

Figure 9A: Comparisons for SPAD reading dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus (-P) treatments; mean of 15 replications per water management and minus-one element combination; asterisk above SPAD reading data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 1% (**) and 5% (*) significance level.

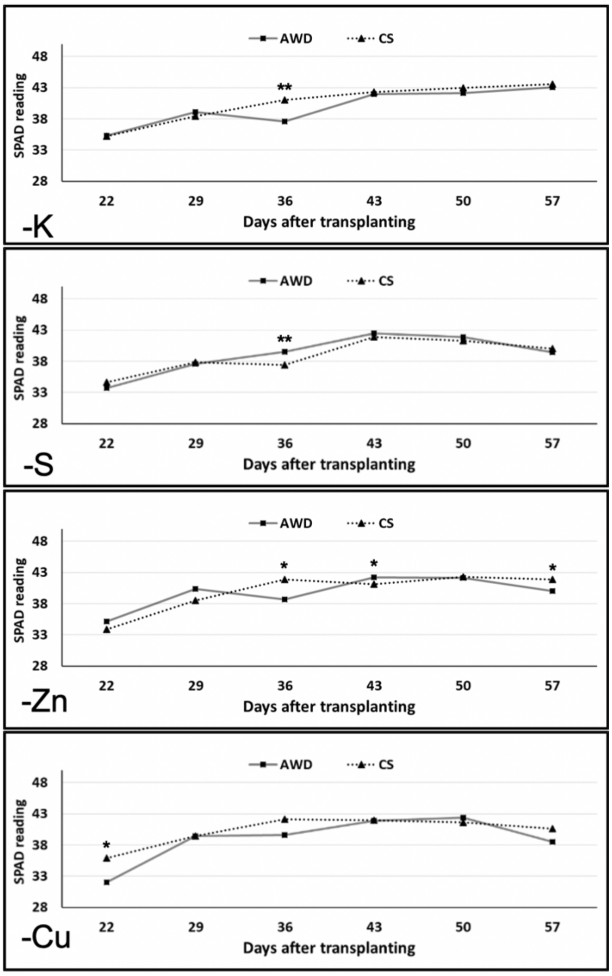

Figure 9B: Comparisons for SPAD reading dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), -zinc (-Zn), and -copper (-Cu) treatments; mean of 15 replications per water management and minus-one element combination; asterisk above SPAD reading data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are higher than CS or vice-versa at 1% (**) and 5% (*) significance level.

S in early stage, 15 kg/ha K in early panicle initiation, and succeeding N additions based on LCC readings. The same nutrient applications are recommended if water level is uncontrollably high; but seedlings should be dipped in 2% Zn oxide solution before transplanting, or 9 kg/ha Zn should be topdressed at 14 DAT. Additional K fertilizer can be applied if rice, particularly those under CS, exhibit K deficiency. Grain yields of PSB Rc 82, applied with recommended fertilizers, should be compared for AWD versus CS in screenhouse and field conditions. Other varieties recommended in Agusan should also be tested.

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CONFLICTS OF INTEREST

There is no conflict of interest.

CONTRIBUTION OF INDIVIDUAL AUTHORS

Author	Contribution
Jehru C. Magahud	conception and design acquisition, analysis and interpretation of data drafting and revising paper for important intellectual content final approval of version to be published accountable for the accuracy or integrity of the paper acquisition of funds
Sheena Lourdes P. Dalumpines	acquisition of data drafting and revising paper for important intellectual content final approval of version to be published accountable for the accuracy or integrity of the paper
Agapito E. Lincuna, Jr.	conception and design acquisition of data final approval of version to be published accountable for the accuracy or integrity of the paper
Gerardo F. Estoy, Jr.	revising paper for important intellectual content final approval of version to be published accountable for the accuracy or integrity of the paper acquisition of funds

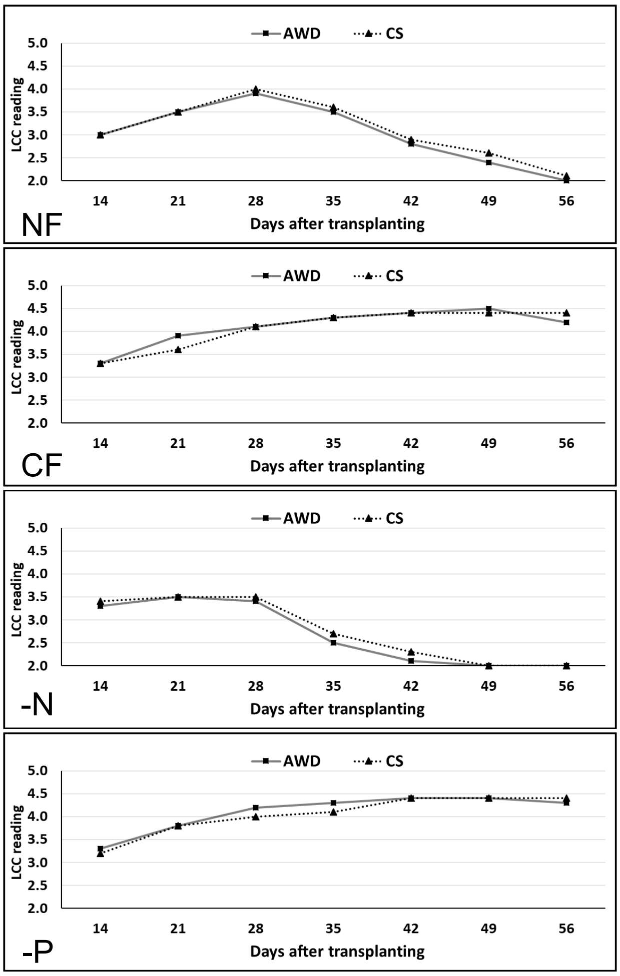

Figure 10A: Comparisons for leaf color chart (LCC) reading dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), and -phosphorus treatments; mean of 5-15 replications per water management and minus-one element combination.

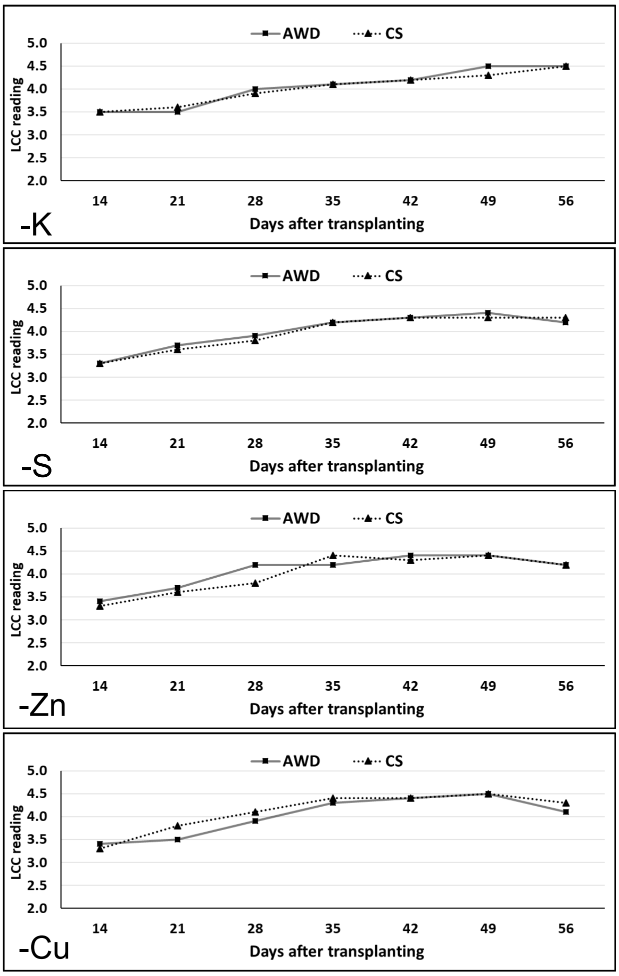

Figure 10B: Comparisons for leaf color chart (LCC) reading dynamics of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in -potassium (-K), -sulfur (-S), -zinc (-Zn), and -copper (-Cu) treatments; mean of 5-15 replications per water management and minus-one element combination.

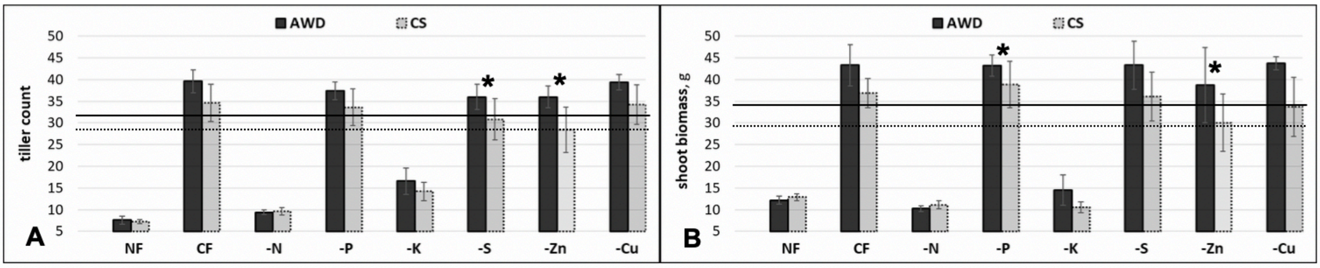

Figure 11: Comparisons for tiller count (A) and oven-dry shoot biomass (B) during harvest of rice under alternate wetting and drying (AWD) vs. those under continuous submergence (CS) in no fertilizer (NF), complete fertilizer (CF), -nitrogen (-N), -phosphorus (-P), -potassium (-K), -sulfur (-S), zinc (-Zn), and -copper (-Cu) treatments; bars above horizontal lines indicate nutrient sufficiency, bars below horizontal lines indicate deficiency; mean of five replications per water management and minus-one element combination; asterisk (*) above tiller count and biomass data at particular day after transplanting denotes that, using the Wilcoxon signed ranks test, data for AWD are significantly higher than CS or vice-versa.

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