Session 1.
Soil Fertility and Crop Nutrient Management

Role of Yield Potential and Yield-Gap Analyses on Resource-Use Efficiency Improvement

U. Singh,[1] M. Aung,[2] and J. Fugice[1]

[1] Fertilizer Research Division, IFDC, Muscle Shoals, Alabama, USA

[2] Fertilizer Sector Improvement Project, IFDC, Yangon, Myanmar

Abstract

A systems approach is used to show the effect of genotypic, environmental, and management factors on the potential yield of rice and maize and the role yield potential and yield-gap analyses play in fertilizer recommendations. Examples from Myanmar are presented for determining yield potential, conducting yield-gap analyses, and identifying appropriate management strategies taking into consideration climatic, soil, and management inputs. CERES-Rice and CERES-Maize models were used to simulate yield potential and N response using site-specific weather and soil data from 18 locations in Myanmar. Planting dates typical for the wet and dry seasons were used for each of the locations. To capture the effect of weather variations, 18 weather years (1997-2015) for each location were used in the simulation study. The wet season rainfed potential production yield, which was the same as the potential production yield, varied from 6.5-7.3 tons per hectare (t/ha) in the Delta Region to 9.4-10.3 t/ha in the Central Dry Zone and Shan State for high-yielding hybrid rice. Similar differences for maize were also observed with the wet season rainfed maize potential production yield of 4.0-4.9 t/ha in the Delta Region and 6.8-7.2 t/ha in the Central Dry Zone and Shan State for the improved maize variety. The potential production yield for irrigated dry season rice was an average of 11.1 t/ha for the 18 locations. The irrigated maize yield potential for the dry season ranged from 6.9-7.6 t/ha in the Delta Region to 7.0-8.6 t/ha in the Central Dry Zone and Shan State. The lower yields in the Delta Region compared to others, particularly during the wet season, were attributed to lower solar radiation. Nitrogen (N) response varied with season, yield potential, and indigenous N supply. Due to these differences, optimum N rates varied from 40 to 120 kilograms (kg) N per ha for rice during the wet season. The optimum agronomic N rates during the dry season were much higher at 120-180 kg N/ha for irrigated hybrid rice. The effects of varieties, indigenous N supply, and method of N application on N recommendations were also simulated.

Introduction

Sustainable intensification is needed for Myanmar's agriculture to meet the challenge of increased demand, improved environmental sustainability, and economic efficiency while operating under increased climatic risks. The agriculture sector contributes 24% to gross domestic product (GDP) and 24.6% to export earnings and employs 61.2% of the labor force (MGI, 2013). A key component of sustainable intensification is achieving more agricultural production on the existing agricultural land. Most Asian countries have experienced significant advancements in agricultural production through intensification. In Myanmar, agricultural production is driven by both the changes in cultivated area and yield per unit area. Low nutrient application, especially of inorganic fertilizer, estimated at a national average of 5-20 kg/ha compared with the world average of about 100 kg/ha, is among the major factors contributing to low and declining agricultural productivity (Lwin et al., 2013). The low rate of fertilizer application is a major contributing factor to low rice yield (Naing et al., 2008). The low productivity of the agriculture sector is reflected in output of only \$1,300 per year per worker compared to \$2,500 in Thailand and Indonesia (MGI, 2013).

Although low rates of fertilizer application may explain the low rice yields at 3.3 t/ha in Myanmar, rice yields vary across Asia from 2 to 15 t/ha due to variety and location (Jing et al., 2008; Ying et al., 1998). Yield for any given crop is the outcome of the effect and interactions of genotype (cultivar characteristics), environment (climatic and soil), and management. Also, yield variances for major food crops in important agricultural areas, such as maize in the USA and Eastern Africa or wheat in Europe and North America, are on the rise (Xu et al., 2016; Ilzumi and Ramankutty, 2016; Trnka et al., 2014). In Myanmar, 15% of the arable land under rice cultivation is challenged by weather-related environmental factors including flooding, drought, and salinity (MOALI, 2015). Hence, insights into the relative importance of genotype, environment, and management are critical for improved yields, increased resource use efficiency, and reduced losses. Myint et al. (2017) reported rice yields ranging from 3.1 t/ha to 6.4 t/ha in the Delta Region of Myanmar, without any N fertilizer application, indicating yields were affected by indigenous soil N supply. This further highlights that yield potential, yield gap, and fertilizer recommendations are site-specific. Myanmar's wide range of agro-environments (soils and climatic conditions) also reinforces the need for site-specific recommendations.

Yield gap is defined as the difference between potential or target yield under optimum conditions and the current farmer's yield. For example, based on current yield of 3.78 and 3.61 t/ha and target yield of 5.16 and 4.93 t/ha, a yield gap of 1.38 and 1.32 t/ha for rice and maize, respectively, was reported by the Japan International Cooperation Agency (JICA, 2013). Another approach is to use simulation models to obtain the potential production yield as the upper ceiling for reference yield. The potential production approach allows one to determine areas with low and high yield ceilings and provides opportunities for improved returns on investment (Singh et al., 2002). As shown in Figure 1, rainfed potential yield for maize changed with planting dates for northeastern Uganda while yield was unaffected in southern Uganda. The fertilizer demand and the returns on fertilizer applications on maize during the September planting will be greater in southern Uganda.

In this paper, we present reducing the yield gap approach to increased agricultural production on the existing agricultural land. A simulation approach using CERES-Rice and CERES-Maize in the Decision Support System for Agrotechnology Transfer (DSSAT) program (Jones et al., 2003) is used for obtaining potential production for rice and maize in three areas of Myanmar: the Delta Region, Shan State, and the Central Dry Zone. The models were also used to determine nitrogen response for rice and maize for the various locations during both the wet and dry season. The findings of the paper highlight the multitude of factors that affect crop production, yield and yield potential, and N management.

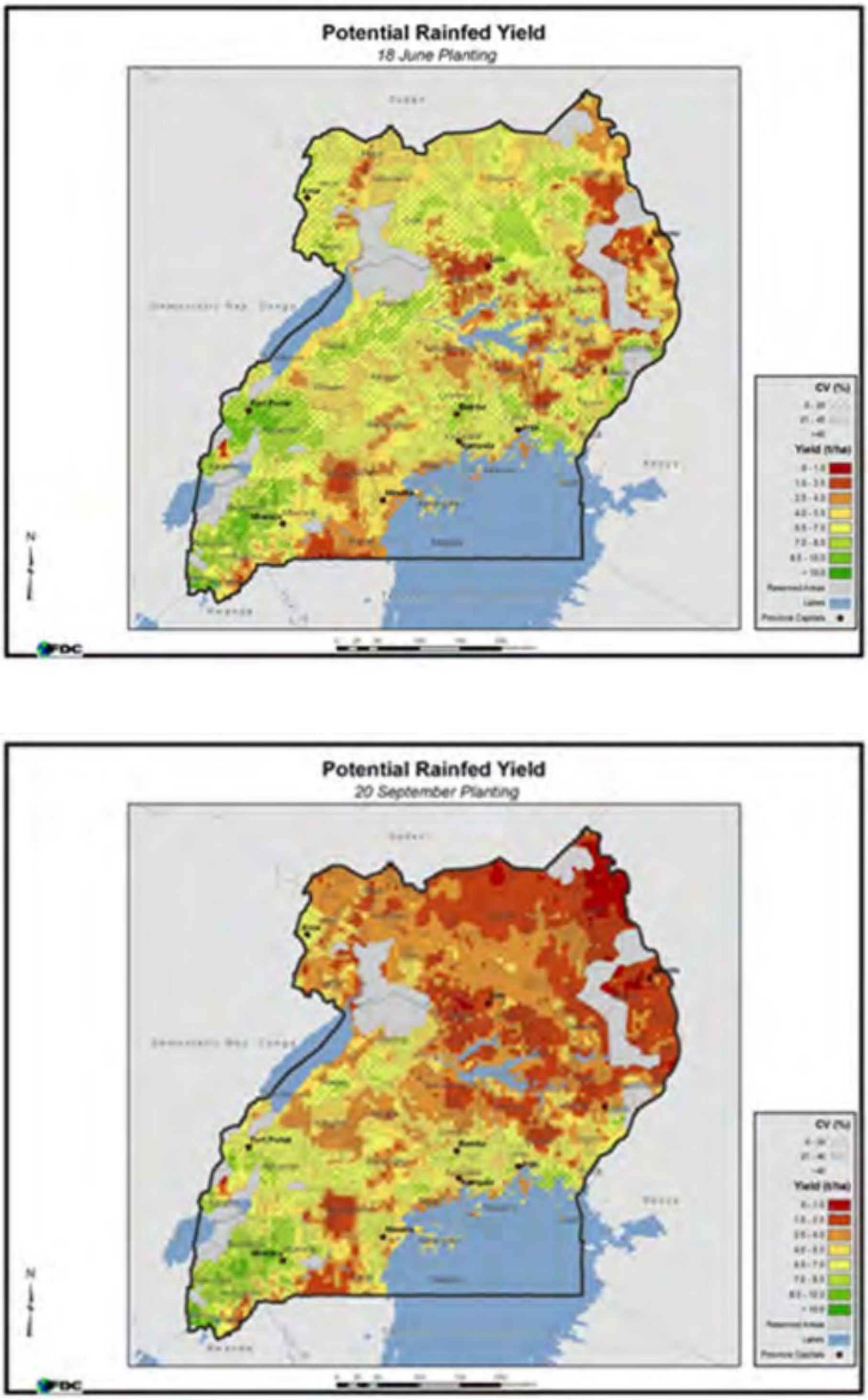

Figure 1. ***Effect of planting date on rainfed-limited potential production yield for maize in Uganda.***

Methods

Model and Data Requirements

The potential yield and the yield responses were derived using the CERES-Rice and CERES-Maize models available through the DSSAT program (Tsuji et al., 1994). The crop models require daily weather data for rainfall, maximum and minimum temperature, and solar radiation. The rainfall, maximum temperature, and minimum temperature were obtained from Myanmar Meteorology Department, and the solar radiation was based on NASA Prediction of Worldwide Energy Resources (POWER) data (https://power.larc.nasa.gov/new/). Soils data were based on the Harmonized World Soil Database (HWSD). HWSD is a global soil database established jointly by the International Institute for Applied Soil Analysis (IIASA) and the Food and Agriculture Organization (FAO) of the United Nations in partnership with ISRIC-World Soil Information, the European Soil Bureau Network, and the Institute of Soil Science, Chinese Academy of Sciences.

The following 18 locations, representing the Fertilizer Sector Improvement (FSI) project and Livelihoods and Food Security Trust (LIFT) Fund field sites, were selected: Aungban, Ayeyarwady, Daik U, HeHo, Kalaw, Kungyangon, Kyaiklat, Letpadan, Ma Gyi Gone, Mandalay, Myaungmya, Naypyitaw, Pakokku, Pindaya, Taik Kyi, Thanatpin, Twantay, and Yangon. To capture the effect of weather variation, 18 years of weather data (1997-2015) were used to determine the mean and standard deviation on yield potential and N response.

Wet and Dry Season Simulations

Although in reality maize may not be grown during the wet season in the Delta Region or rice in the Central Dry Zone during the dry season, simulations for both rice and maize were done for all 18 locations during both the wet and dry season planting. The planting dates were 15 June and 15 December for the Delta Region and 30 June and 30 January for the Central Dry Zone and Shan State, respectively, for wet and dry season rice. The corresponding dates for maize were 15 June and 1 November for the Delta Region and 30 June and 21 December for the Central Dry Zone and 1 June and 1 December for Shan State, respectively, for wet and dry seasons. For the N response simulation, urea was applied using the conventional broadcast application method. Genetic coefficients representative of hybrid rice and improved maize varieties were used for both seasons. Although both the CERES-Rice and the CERES-Maize models have been evaluated in similar environments (Jones et al., 2003; Timsina and Humphreys, 2006; Basso et al., 2016), they were used for the first time in Myanmar in this study. Additional treatments highlighting the effects of soil fertility, cultivars, and urea deep placement (UDP) on yield and N response were simulated.

Yield Potentials

Potential production yield is defined as the yield obtained when crop production is not limited by water, nutrients, or any other biological stress (production situation 1 in Figure 2), hence the effects of soil properties, rainfall, and pests and diseases were not simulated. However, the effects of temperature, radiation, planting date, planting density, and variety were simulated. Rainfed potential yield took into account the effect of water limitation as influenced by rainfall and soil properties (water holding capacity, percolation rate, and runoff) as shown in production situation 2 of Figure 2. This will be the equivalent of an experiment conducted under rainfed conditions in which all nutrients were applied and complete care was taken to control pest and disease incidences. The N response simulations captured the effect of weather and soils, including N limitations; however, other nutrients were assumed to be non-limiting.

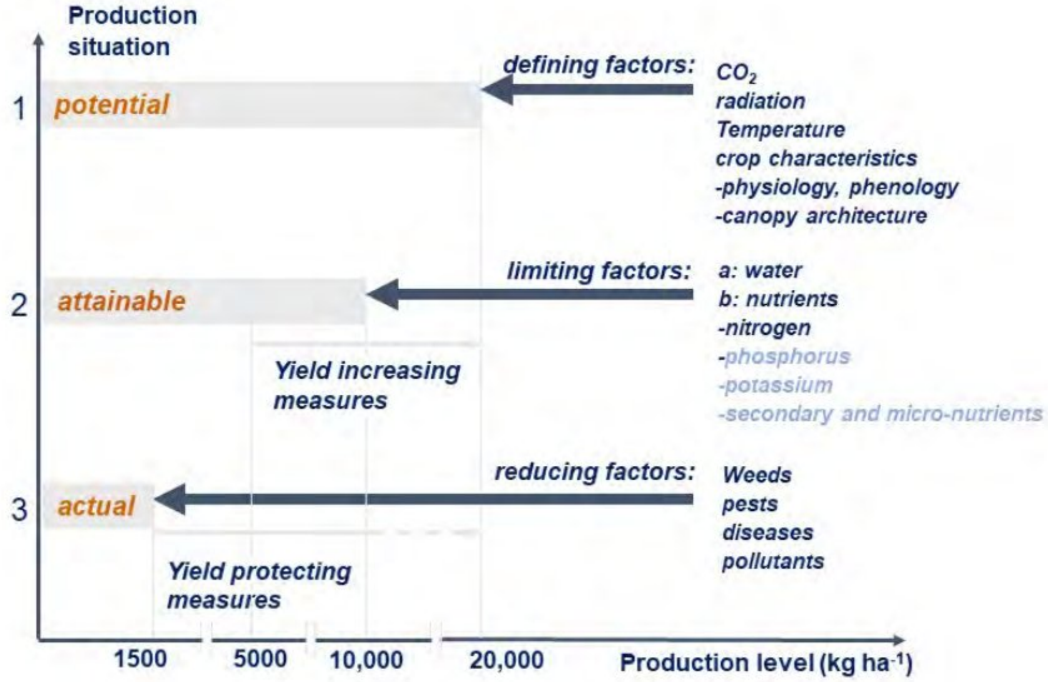

Figure 2. Simulating potential and attainable yield using CERES-Rice and CERES-Maize models.

Results

Yield Potential and Nitrogen Response for Wet Season Rice

The potential yield and the rainfed potential production yield for wet season rice were the same for all locations, indicating that water was not the limiting factor (Figure 5). The average rainfall during the growing season ranged from 845 millimeters (mm) in the Central Dry Zone and Shan Sate to 1,590 mm in the Delta Region. The mean rainfed potential yield ranged from 6.5-7.3 t/ha in the Delta Region (shaded section) to 9.4-10.3 t/ha in the Central Dry Zone and Shan State (Table 1). As evident from the low variance (standard deviation of 0.5 t/ha), the effect of weather variation over the past 18 weather years (1997-2015) was minimal on the rainfed potential production yield.

The response to N fertilizer application was influenced both by the yield potential and the initial N status (Figure 3). The relatively high simulated yields without N application (0 N) compared to average reported yield of rice shows the dependence of yield and fertilizer recommendation on soil properties and the need for reliable soil data. Soil organic matter content was generally high because it were based on soil samples from at least 10 years ago. In the high-yielding environments (Shan State and the Central Dry Zone), N rates of more than 120 kg N/ha was needed to approach the potential yield. In Daik U, a relatively low-yielding environment, additional application of N beyond 100 kg N/ha gave little incremental yield increase to achieve the potential yield. As shown in Figure 3, the agronomic optimal N recommendation varies with locations (soil properties and weather). The average daily solar radiation during the rice wet season ranged from 12.5 megajoules per square meter a day ($MJ/m^2/day$) in Twantay and Kyaiklat to 17.2 $MJ/m^2/day$ in Pakokku and, on average, the solar radiation was 13.1 $MJ/m^2/day$ in the Delta Region compared with 16.5 $MJ/m^2/day$ in the Central Dry Zone and Shan State. This explains the significantly higher yield potential in the Central Dry Zone and Shan State than in the Delta Region.

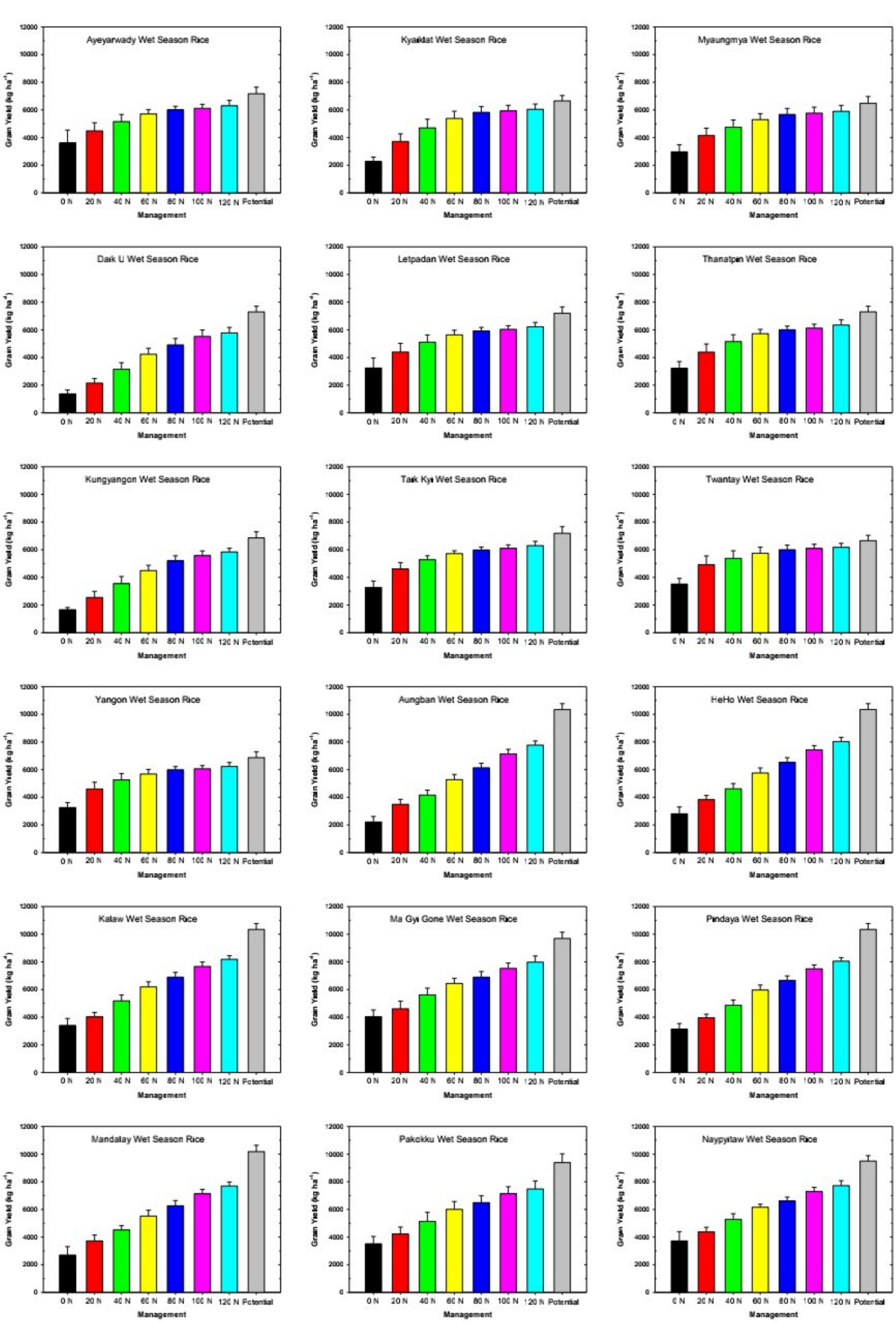

Figure 3. Simulating potential and attainable yield for wet season rice.

Yield Potential and Nitrogen Response for Dry Season Rice

The mean dry season potential production yield for rice ranged from 9.8 to 13.5 t/ha with the average of 11.1 t/ha for the 18 locations (Table 1). The differences in potential yield among the different zones were not as dramatic as in the wet season rice. However, the variation in the potential yield at any given location was much higher compared to the wet season. The same rice variety was used for both seasons. The rainfed potential production yield for dry season rice, on residual soil moisture (no cropping during the wet season) and late rainfall, ranged from 1.5 t/ha to 6.1 t/ha. The simulated yield was higher than expected because drought stress during vegetative stress prolonged the growing season, on average, by 56 days, allowing the rice crop to capture the early monsoon rain (Table 1). However, as evident from ongoing cultural practice, rainfed dry season rice is not practical for most places in Myanmar.

***Table 1.	Potential yield and duration to anthesis for rice.***

	Potential Yield (t/ha)				Duration to Anthesis (days after planting)		
Location	Wet Season-Rainfed		Dry Season-Irrigated		Wet Season	Dry Season	
	Mean	Std Dev	Mean	Std Dev	Rainfed	Irrigated	Rainfed
Ayeyarwady	7.18	0.47	11.21	1.25	64	72	136
Kyaiklat	6.65	0.39	10.58	1.45	63	68	124
Myaungmya	6.48	0.49	11.28	1.27	62	69	115
Daik U	7.29	0.43	10.67	1.14	65	70	123
Letpadan	7.2	0.46	11.21	1.25	64	72	129
Thanatpin	7.3	0.41	10.67	1.14	65	70	128
Kungyangon	6.86	0.44	10.25	0.75	63	66	119
Taik Kyi	7.19	0.48	11.21	1.25	64	72	128
Twantay	6.65	0.39	10.58	1.45	63	68	131
Yangon	6.87	0.43	10.25	0.75	63	66	119
Aungban	10.34	0.43	11.74	0.55	74	74	128
HeHo	10.34	0.43	11.74	0.55	74	74	128
Kalaw	10.34	0.43	11.74	0.55	74	74	126
Ma Gyi Gone	9.69	0.45	9.77	0.92	67	66	129
Pindaya	10.34	0.43	11.74	0.55	74	74	129
Mandalay	10.18	0.46	11.60	0.63	73	74	126
Pakokku	9.39	0.64	9.81	0.92	66	66	129
Naypyitaw	9.49	0.39	13.49	0.74	72	86	138

There was a near-linear increase in rice grain yield with increasing N fertilizer rates of up to 180 kg N/ha at all locations (Figure 4). The N response in the Delta Region during the wet and dry season differed as dictated by the yield potential (Figure 5A and 5B). Such large differences are generally not reported in field trials, perhaps due to inadequate irrigation and other nutrient limitations during the dry season. The rice production in Shan State and the Central Dry Zone are similar between the wet season rainfed rice and the dry season irrigated rice (Figure 5C and 5D).

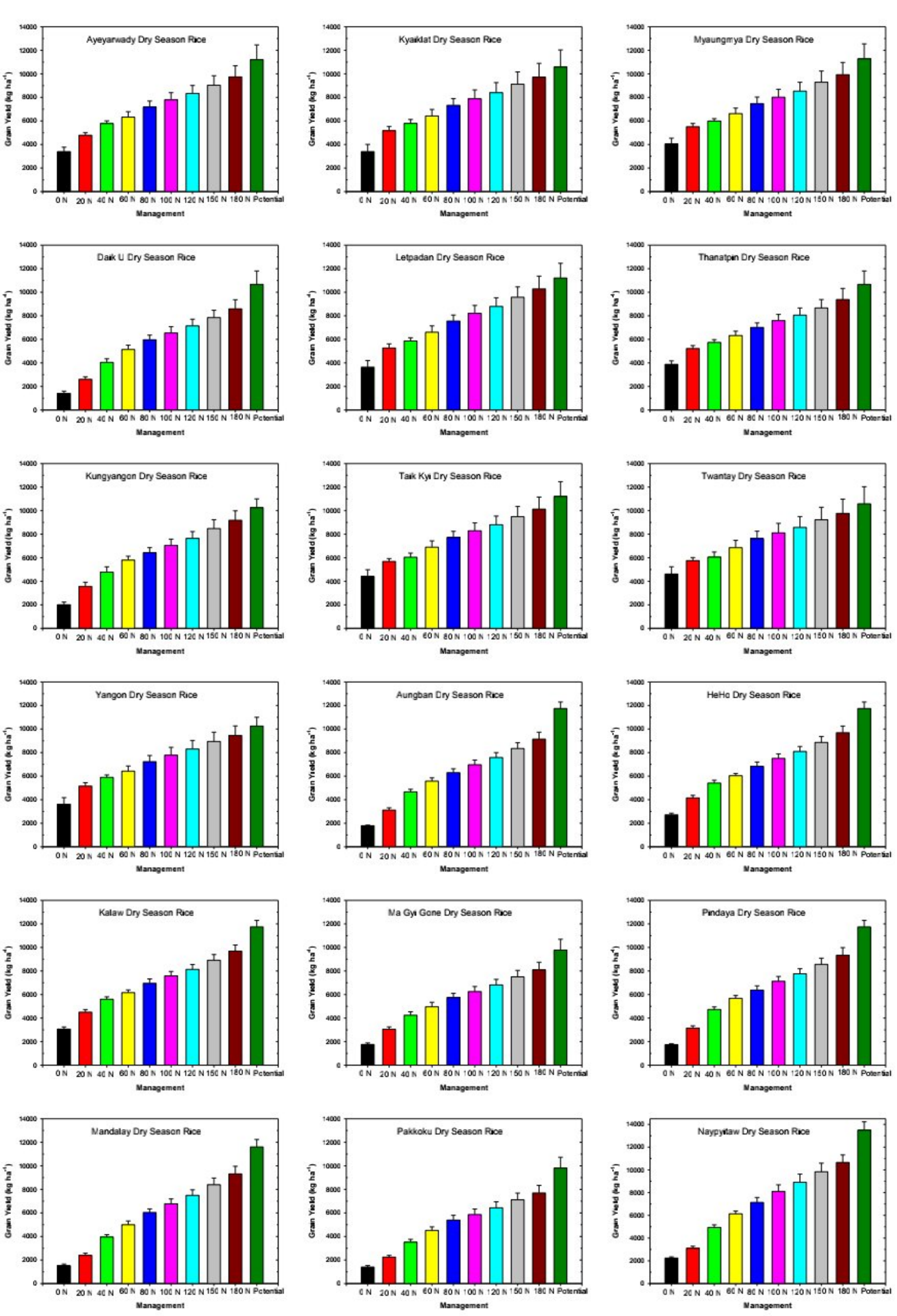

Figure 4. Simulating potential and attainable yield for dry season rice.

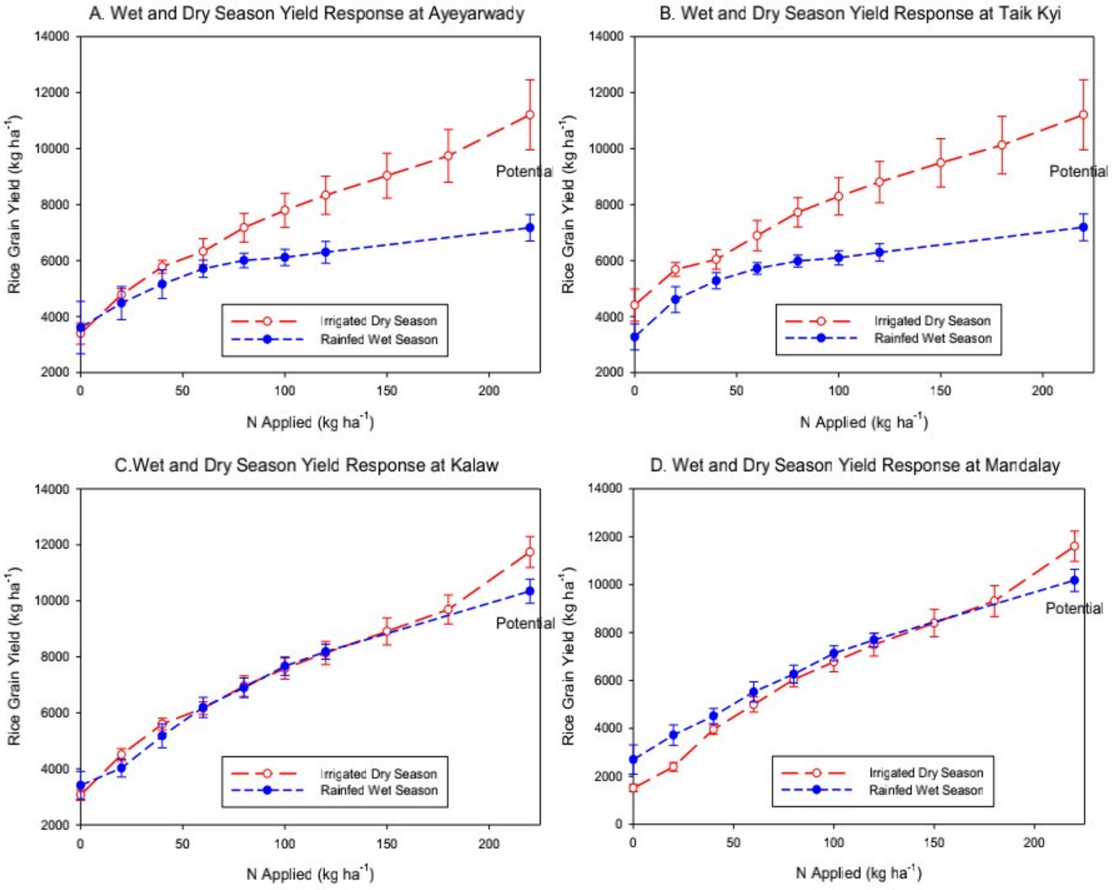

Figure 5. **Comparison of N response on wet and dry season rice.**

The dry season rainfed rice, even with the extended duration, was risky, with high variations from year-to-year and no response to N application (Figure 6). The irrigated dry season rice, in contrast, was high yielding, low in variance, and highly N responsive across all locations (Figures 4-6). The amount of N fertilizer required to minimize the yield gap to less than 1 t/ha was 180-200 kg N/ha. However, the N rate can be substantially reduced with urea deep placement as evident from Figure 7. In the high-yielding Aungban site, 150 kg N/ha deep-placed gave 17% higher yield compared to broadcast application of 180 kg N/ha. Similar increases in yield with savings of N have been reported in field trials in Myanmar and elsewhere (Myint et al., 2017; Miah et al., 2016). In a simulated N response to achieve a similar yield of 9.4 t/ha for irrigated dry season rice at Yangon, N fertilizer requirements ranged from 180 kg N/ha for broadcast application to 100 kg N/ha for UDP (Figure 7).

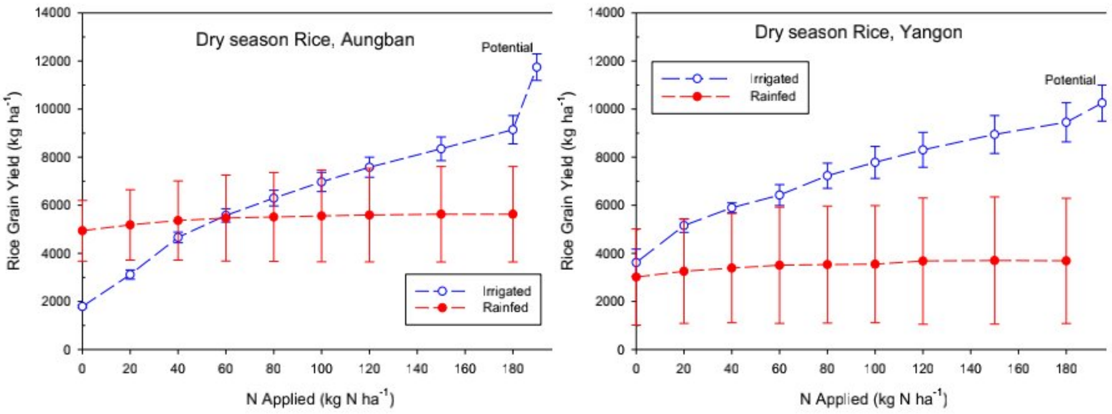

Figure 6. Comparison of N response on irrigated and rainfed dry season rice.

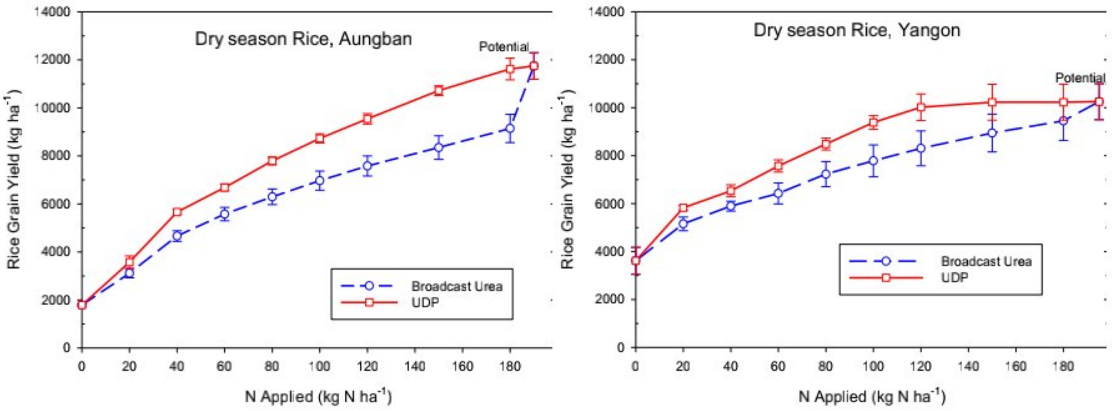

Figure 7. Comparison of N response with broadcast urea and UDP.

Yield Potential and Nitrogen Response for Maize

Simulated rainfed maize potential production during the wet season, as with rice, was lower in the Delta Region with a mean yield of 4.5 t/ha compared to 7.0 t/ha in the Central Dry Zone and Shan State (Table 2). Since the simulated yields do not take into account the effect of pests and diseases, the actual maize yields in the Delta Region would likely be severely depressed during the wet season with high pest and disease incidences. While the CERES-Maize model simulates the effect of flooding and saturated water content on maize crop, it does not simulate the lateral movement of water, a common occurrence during the wet season in the Delta Region. This additional water in the fields would have correctly resulted in the model predicting lower maize yields.

Table 2. Potential yield for maize.

Location	Maize Potential Yield (t/ha)					
	Wet Season-Rainfed		Dry Season-Irrigated		Dry Season-Rainfed	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Ayeyarwady	4.60	0.78	7.64	0.86	1.89	0.77
Kyaiklat	4.14	0.55	7.06	1.19	3.46	1.10
Myaungmya	3.95	0.87	7.42	0.91	4.48	1.35
Daik U	4.86	0.63	7.22	0.91	2.88	0.69
Letpadan	4.61	0.78	7.64	0.86	4.53	0.89
Thanatpin	4.88	0.62	7.22	0.91	4.00	0.74
Kungyangon	4.42	0.54	6.90	0.69	2.74	1.11
Taik Kyi	4.61	0.78	7.64	0.87	4.35	0.89
Twantay	4.14	0.55	7.06	1.19	4.04	1.23
Yangon	4.42	0.54	6.90	0.69	4.97	1.21
Aungban	6.95	0.74	8.64	0.51	0.42	0.55
HeHo	6.95	0.74	8.64	0.51	0.74	0.55
Kalaw	6.95	0.74	8.64	0.51	0.65	0.52
Ma Gyi Gone	7.01	0.87	6.78	0.86	1.50	0.50
Pindaya	6.95	0.74	8.64	0.51	0.63	0.51
Mandalay	7.19	0.48	7.69	0.98	0.70	0.38
Pakokku	6.96	0.52	7.11	1.19	0.78	0.29
Naypyitaw	6.74	0.74	8.76	0.76	3.76	0.78

The dry season irrigated maize potential production was 7.3 t/ha in the Delta Region and 7.9 t/ha in the other locations. On the other hand, simulated yield potential under rainfed conditions for the dry season maize, even with the build-up of residual moisture, was unsustainable in the Central Dry Zone and Shan State with mean yield of 0.8 t/ha and standard deviation of 0.5 t/ha (Table 2). In the Delta Region, the yields ranged from 1.9 to 5.0 t/ha. The soils data with higher organic matter content than reality could have influenced both the soil fertility and water-holding capacity, particularly for deep-rooting crops such as maize, resulting in crop growth and reasonable yield on residual moisture with limited rainfall.

The variation in N response across the locations both during the wet season for rainfed maize (Figure 8) and during the dry season for irrigated maize (Figure 9) highlighted the effect of indigenous N supply (soil property) and yield potential (weather and variety). The yield variation from less than 1.0 to 6.9 t/ha without N application clearly indicates the need for up-to-date and reliable soil data. The seasonal and soil fertility effects on N response and N fertilizer recommendations are presented in Figure 10. Thus, fertilizer recommendations must consider both site and seasonal effects. The choice of maize variety will also influence N response and N recommendations. As simulated results in Figure 11 showed, higher N rates would be more lucrative for hybrid maize with higher yield potential than the improved maize variety used in this study.

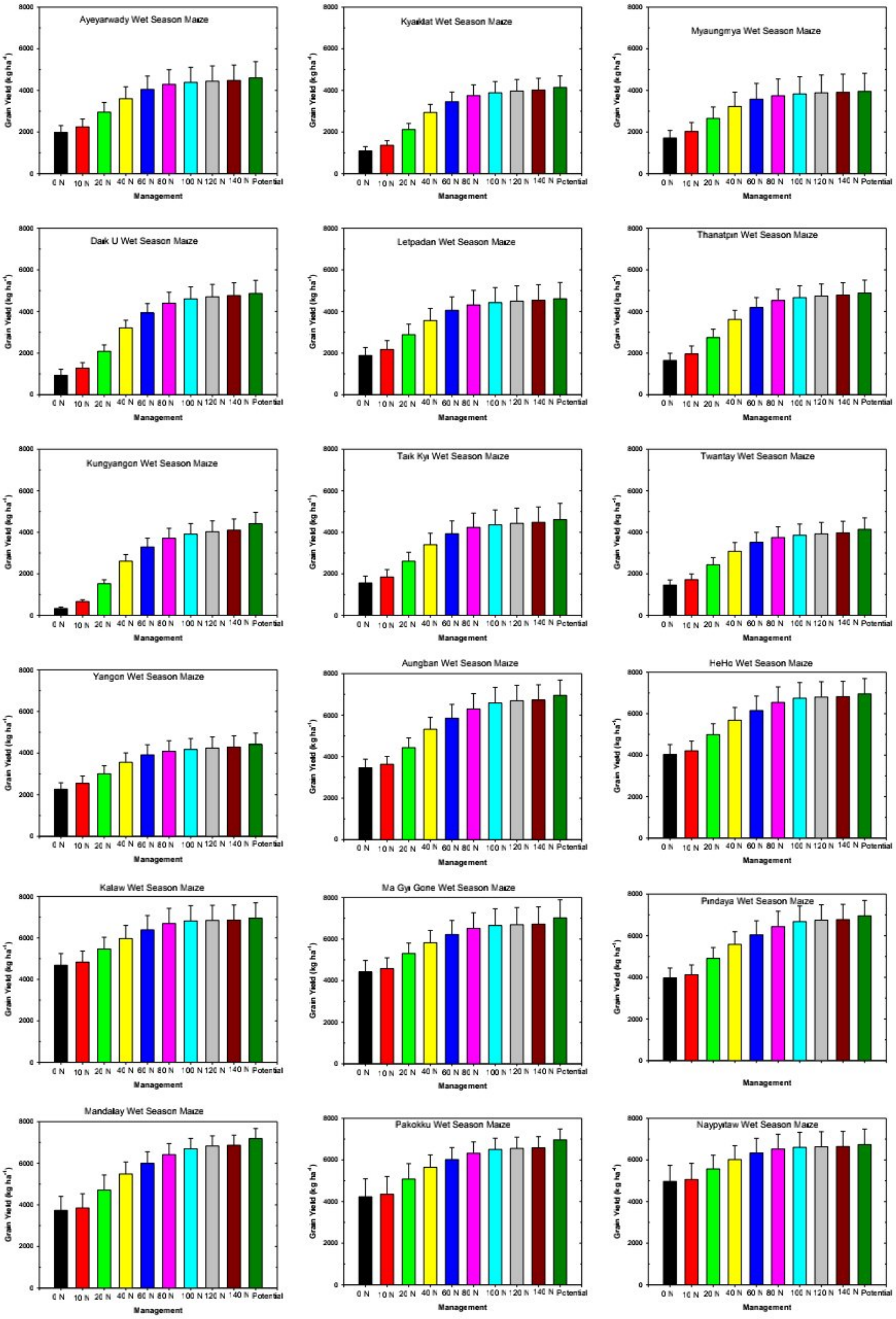

Figure 8. Simulating potential and attainable yield for wet season maize.

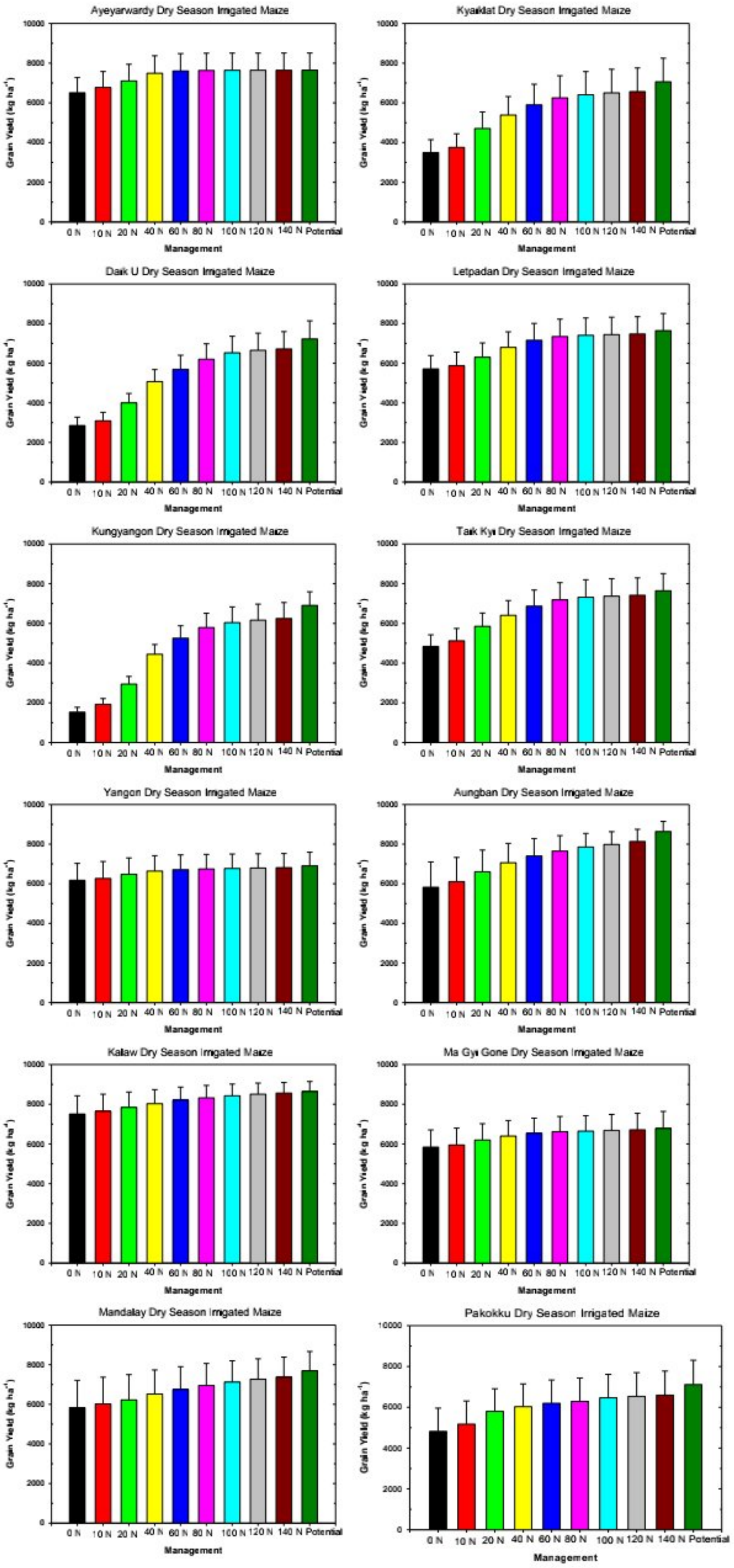

Figure 9. Simulating potential and attainable yield for dry season irrigated maize.

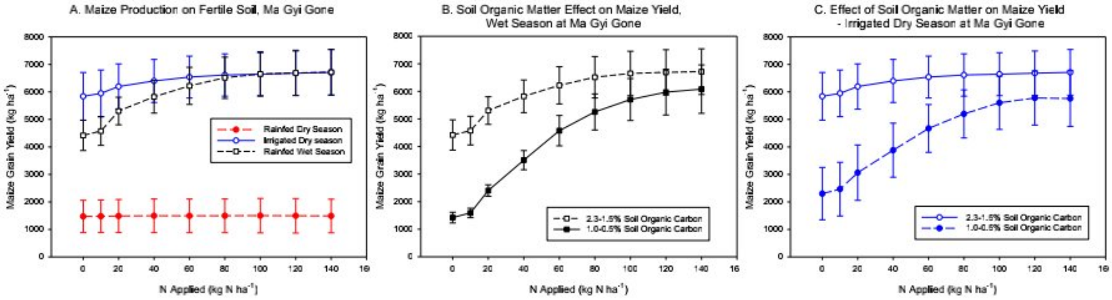

Figure 10. Comparing effect of season, irrigation, and soil fertility on maize yield.

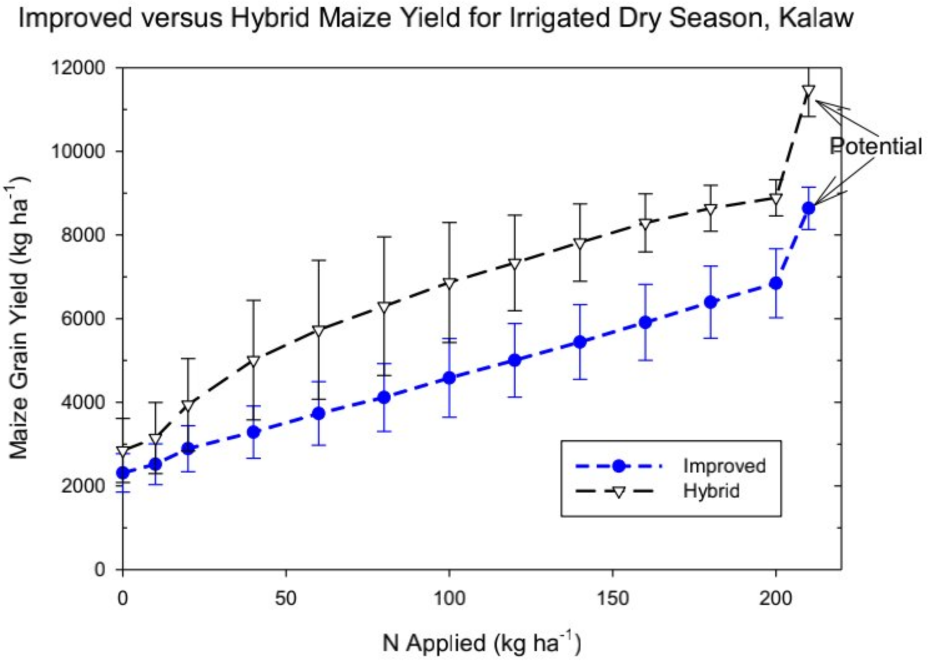

Figure 11. Comparing effect of maize variety on N response and yield potential.

Conclusion

Potential yield determination provides the opportunities and constraints for growing a crop in a given environment. The constraints may be overcome with changes in management such as investment in irrigation or simply identifying appropriate varieties and planting dates. Other conditions may require a more drastic change, such as growing a different crop or switching from annual to perennial crop or even agroforestry. The yield gap between the potential yield and attainable yield and more so between the potential and farmer yield provides opportunities for intensification and identifying likely yield-limiting constraints.

The large differences in yield potential for wet season rainfed rice and irrigated dry season rice in the Delta Region than those reported provide opportunities to identify limiting factors and reduce the yield gap for dry season rice. The differences in maize and rice yield potential due to seasons and locations highlight the importance of weather conditions and planting dates as major potential yield-determining factors. For example, 3.4 MJ/m^2/day higher solar radiation in the Central Dry Zone than that in the Delta Region over 100+ days of active crop growth can significantly increase the yield potential.

The changes in N response function was dictated by both the yield potential and the indigenous N supply. N application as UDP was shown to be more efficient than broadcast application. The importance of soil testing for providing current and reliable soil data for fertilizer recommendations is amply evident. Effective agricultural intensification therefore requires a concerted effort to incorporate site-specific soils and weather data. Decision support tools can improve the efficiency of agricultural research and technology transfer; however, as with any other tools, they need to be evaluated under Myanmar conditions.

References

Agyin-Birikorang, S., J. Fugice, U. Singh, J. Sanabria, and S. Choudhuri. 2017. "Nitrogen Uptake Kinetics for Key Staple Cereal Crops in Different Agro-Ecological Regions of the World," *Journal of Plant Nutrition*, 40(7):995-1023.

Basso, B., L. Liu, and J.T. Ritchie. 2016. "A Comprehensive Review of CERES-Wheat, -Maize and -Rice Models' Performances," *Advances in Agronomy*, pp. 27-132.

Ilzumi, T., and N. Ramankutty. 2016. "Changes in Yield Variability of Major Crops for 1981-2010 Explained by Climate Change," *Environ. Research Letter*, doi:1088/1748-9326/11/3/034003.

Jing, Q., B. Bouman, H. van keulen, H. Hengsdijk, W. Cao, and T. Dai. 2008. "Disentangling the Effect of Environmental Factors on Yield and Nitrogen Uptake of Irrigated Rice in Asia," *Agricultural Systems*, 98.177-188.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. "The DSSAT cropping system model," *European Journal of Agronomy*, 18:235-265.

Lwin, H.Y., T. Myint, S. Than, N.M. Aung, C.C. San, and T. Htut. (2013). *Role of Fertilizer Policy in Transforming Agriculture of Myanmar*, Department of Agricultural Economics, Yezin Agricultural University, Yezin, Nay Pyi Taw, Myanmar.

Miah, M.A.M., Y.K. Gaihre, G. Hunter, U. Singh, S.A. Hossain. 2016. "Fertilizer Deep Placement Increases Rice Production: Evidence from Farmers' Fields in Southern Bangladesh," *Agronomy Journal*, 108:1-8.

MOALI. 2015. *Myanmar Rice Sector Development Strategy: Building the Foundation of a Modern, Industrialized Nation, through Inclusive Agricultural and Rural Development*, Ministry of Agriculture and Irrigation, Myanmar.

Naing, T.A.A., A.J. Kingsbury, A. Buerkert, and M.R. Finckh. 2008. "A Survey of Myanmar Rice Production and Constraints," *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 109:151-168.

Singh, U., P.W. Wilkens, W.E. Baethegen, and T.S. Bontkes. 2002. "Decision Support Tools for Improved Resource Management and Agricultural Sustainability," IN L.R. Ahuja, L. Ma, and T.A. Howell (Eds.), *Agricultural System Models in Field Research and Technology Transfer*, pp. 91-117, Lewis Publishers, Boca Raton, Florida, USA.

Timsina, J., and E. Humphreys. 2006. "Applications of CERES-Rice and CERES-Wheat in Research Policy, and Climate Change Studies in Asia: A Review," *International Journal of Agric. Res.*, (1)3:202-225.

Trnka, M., R.P. Rotter, M. Ruiz-Ramos, K-C. Kersebaum, J.E. Olesen, and M.A. Semenov. 2014. "Adverse Weather Conditions for Wheat Production in Europe Will Become Frequent with Climate Change," *Nature Climate Change*, 4:637-643.

Tsuji, G.Y., G. Uehara, and S. Balas. 1994. *DSSAT V.3: A Decision Support System for Agrotechnology Transfer*, University of Hawaii, Honolulu.

Xu, H., T.E. Twine, E. Girvetz. 2016. "Climate Change and Maize Yield in Iowa," PLoS ONE 11(5): e0156083, doi:10.1371/journal.pone.0156083.

Ying, J., S. Peng, Q. He, H. Yang, G. Yang, R. Visperas, and K. Cassman. 1998. "Comparison of High-Yield Rice Tropical and Subtropical Environments – I. Determinants of Grain and Dry Matter Yields," *Field Crops Res.*, 57:71-84.