The Role of Mineral Fertilizers in Climate-Resilient Agriculture: Focus on Myanmar

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Abstract

The use of mineral fertilizers has permitted at least 50% of global food production. However, use of fertilizers could have negative environmental consequences contributing to climate change. Climate change is thought to be partly responsible for increases in abiotic and biotic perturbations that negatively impact crop production. Impacts of climate change, such as an increase in incidences of flooding, drought, salinity, and crop disease, are noted for Myanmar. However, appropriate use of existing nitrogen (N) fertilizers, development of new N fertilizers with improved uptake efficiency, and the balancing of fertilizer composition to include secondary and micronutrients can mitigate both the contribution of fertilizer to climate change and the impact of climate change in agriculture. This paper addresses the role of fertilizers in a changing climate where drought, salinity, pests, and incidences of diseases are heightened. Strategies to enhance fertilizer use efficiency toward engendering a climate-resilient production system are discussed for rice, the predominant crop in Myanmar.

1. Introduction

Agricultural production in most Asian countries has experienced significant advancement in the last decades. In Myanmar, agricultural crop production is dominated by rice, occupying more than 60% of the country's arable land, mostly in lowland production systems. Rice production in Myanmar over the years has been characterized by episodes of high and low production cycles, increasing from about 21 million (M) tonnes (t) in 2000 to about 33 Mt in 2010, before declining to about 26 Mt in 2014. This trend is related to changes in cultivated land area (hectares) and rice yield per hectare. Fertilizer use has been identified as being important for increasing and sustaining rice production in Myanmar (Naing et al., 2008). However, fertilizer use in Myanmar has historically been relatively low (Ricepedia, data accessed August 2017). Between 2005 and 2013, fertilizer use on rice increased from 6,520 t to 16,830 t. A study conducted during 2000 and 2001 indicated that low rates of fertilizer application, particularly N and, to a lesser degree, P and K, is a major contributing factor to low yield in rice (Naing et al., 2008). Notably, fertilizer use in 2014 increased sharply to between 1.2 and 1.4 Mt (Gregory et al., 2014; FAO, data accessed August 2017). Whether this increase will be sustained remains to be seen. However, there is no question that rice production is crucial to food security in Myanmar and the region and that poor management of rice cropping systems can significantly affect the environment.

A national report indicates that about 15% of Myanmar's arable land under rice cultivation is challenged by weather-related environmental factors including flooding, drought, and salinity (Myanmar RSDS, 2015). Individually or combined, these weather-related events result in considerable yield losses in rice. For example, between 2006 and 2011, record-breaking flood events in different parts of the country caused extensive damage to rice crops, with more than 50% crop and over 1.7 Mt of rice grain losses. Similarly, various drought incidences across the country in 2010 destroyed agricultural yields of various crops, including rice, peas, sugarcane, and tomato. Also, incidences of salinity impacting rice productivity in the Delta region of Myanmar have been reported. Salinity increases attributed to sea level rise and seawater encroachment are expected to intensify due to double cropping of rice in monsoon and summer seasons. However, desalinization efforts to mitigate the impact are being undertaken (Climate Change Alliance, data accessed August 2017; SeinnSeinn et al., 2015).

Nitrogen (N)-based fertilizers, especially urea, account for most of the fertilizer consumed in Myanmar (FAO, data accessed 2017; Gregory et al., 2014) and, by implication, in rice production. However, use of urea is associated with N losses that often exceed 50% of the applied fertilizer (Angle et al., 2017) and potentially contribute to climatic changes that could exacerbate some of the above-mentioned weather events. Taken together, the negative effects of environmental stressors on crop yield, still inadequate levels of infrastructure such as irrigation to mitigate effects from drought, and the huge nutrient losses associated with N fertilizer use in lowland rice production are real or potential factors contributing to hinder growth in rice production in Myanmar. Moreover, high nutrient losses under conditions of low fertilizer use have the potential to significantly impact crop productivity. The objective of this paper is, therefore, to highlight fertilizer and fertilization strategies for sustaining and increasing agricultural crop production in Myanmar in the face of climate change challenges.

Globally, mineral fertilizers have driven much of the improvement in agricultural yields and are responsible for feeding nearly half of the world's human population (Erisman et al., 2009). Accordingly, fertilizer use in Myanmar was identified as a major contributing factor influencing rice production (Naing et al., 2008), a dominant crop with production in lowland systems occupying more than 82% of the total sown area of 7.6 M ha (Myanmar RSDS, 2015). Furthermore, the introduction of fast-growing, high-yielding rice varieties in Myanmar has increased the need for N fertilizer in order to cope with the heightened crop physiological demands associated with improved crop varieties. Consequently, in Myanmar, rice yield increases to 7 t/ha have been reported with NPK application, from less than 3 t/ha in non-fertilized controls, dependent on the rice variety (Matsuda, 2011).

As previously noted, N-based fertilizers account for the majority of fertilizers used in rice production in Myanmar. However, serious N losses can occur in lowland production systems exposed to continuous flooding or alternate wetting and drying (Angle et al., 2017). Notably, of the 19.2 teragram global N-fertilizer input applied to rice, N losses range between 10% and 50% as volatilized ammonia (NH_3), 6% and 50% as leached nitrate (NO_3^-), and <1% as emitted nitrous oxide (N_2O). Globally, only an estimated 36% of the applied N is actually utilized by the rice plant (Coskun et al., 2017). Specifically for Myanmar, total fertilizer (NPK) use efficiency for rice is approximately 27% (Matsuda, 2011). Loss of N from fertilizer contributes to undesirable environmental impacts, such as greenhouse gas (GHG; e.g., N_2O) production and pollution of surface and underground waters (Angle et al., 2017). Production of GHG from N fertilizers directly contributes to climate change; a unit of N_2O is 300 times more potent in trapping heat than the same unit of CO_2, another GHG (Coskun et al., 2017). Climate change is a primary environmental factor that is disruptive to agricultural production in different parts of the globe (Angle et al., 2017), due in part to related severe weather events, including drought, salinity, and flooding. In addition, high N fertilizer use leading to increased plant biomass also leads to high uptake of other essential nutrients by plants, resulting in nutrient mining and eventually to lower yields over time (Jones et al., 2013), in addition to soil and water pollution of NO_3 runoff. Current evidence indicates that appropriately managing N fertilizers, using improved N fertilizers with enhanced N uptake, and balancing the nutrient composition of mineral fertilizers hold strong promise for mitigating N loss and adapting plants to climate change-related incidences, including drought, salinity, and pests and diseases, while improving plant biomass and grain production and, hence, carbon sequestration (Angle et al., 2017; Bindraban et al., 2015; Dimkpa and Bindraban, 2016). There is, therefore, a continuous need to re-examine the role of N fertilizers, in particular, and fertilization strategies, in general, in order to maximize fertilizer benefits and provide resilience to agricultural production systems against a changing climate. Given the recognition by several reports, including those from Myanmar's Ministry of Agriculture and IPCC (summarized by Slagle, 2014), that climate change and associated weather events are significant factors in slowing national development due to attendant losses in the agriculture sector, Myanmar is a good example of countries in dire need of climate-resilient agricultural strategies, such as those that fertilizers engender.

2.1 Fertilizer Functionality under a Changing Climate

Flooding, drought, salinity, reduced nutrient immobility, and increased pest and disease incidences are among the main environmental outcomes of climate change that directly affect crop production. For example, a national crop production decline of 10%, on average, occurs as a result of drought, according to a recent global analysis of extreme weather effects on crop production (Lesk et al., 2016). Drought, salinity, and nutrient immobility are interlinked. Soil salinity levels increase during extended drought periods as less water becomes available in soil to dilute salt. When soil salinity levels are high, water in the root is pulled into the soil through osmosis, depriving the plant of moisture. At the same time, nutrients in soil are increasingly immobilized as water becomes less available, which affects their uptake by plants. In the presence of high sodium (Na), plant-essential metal ions are outcompeted for root binding sites.

Because drought and salinity inhibit plant growth, they indirectly reduce the amount of carbon captured by plants, due to reducing plant leaf area or leaf number available for photosynthesis. Thus, drought and salinity indirectly contribute to increasing the level of CO_2 in the atmosphere. Drying soils also influence the state of N, as mobility and plant accumulation of most nutrients are limited by a low soil solution phase (Dimkpa et al., 2017). Under such conditions, N becomes more prone to atmospheric emission due to several factors, including improvement in soil aeration, enhanced nitrification, and less plant biomass as a sink for N. Emission of N into the atmosphere contributes up to 1.6% of the atmospheric GHG, N_2O (Angle et al., 2017). On the other hand, excessive salinization in soil and corresponding plant accumulation of Na and Cl cause osmotic stress in plants, further reducing available plant water and inhibiting uptake of nutrients. Ultimately, increased salt uptake induces reactive oxygen species production that hampers plant growth (Ashraf et al., 2014).

It has been speculated that due to their large populations, short generation time, and ease of multiplication and dissemination, disease pathogens will likely be among the first organisms to be influenced by climate change. Increase in pest and disease incidences occur with warmer temperatures, as rising temperatures increase pest breeding seasons and reproductive rates and pest overwintering mortality reduces. These scenarios lead, ultimately, to potentially new pest and disease invasions into new areas (Eastburn et al., 2010; Gornall et al., 2010; Pimentel, 1993). Rice production is affected by many pests and diseases that are likely to be influenced by climate change. For example, in Bangladesh, a neighboring country to Myanmar, sheath blight caused by *Rhizoctonia solani*, which was a minor disease in the early 1970s, has now become a destructive disease of rice. Similarly, leaf roller (*Cnaphalocrocis medinalis, Marasmia exigua*) that was not hitherto a prominent rice pest has increased in incidence since the 1980s (Haq et al., 2010). In Myanmar, notably, less than 15% of surveyed rice fields in 2000-2001 were found to be disease-free; sheath blight, bacterial leaf blight, and sheath rot were found to be prevalent (Naing et al., 2008). The interplay among crop abiotic and biotic factors related to climate change clearly has far-reaching consequences for human food security under a changing climate and warrants the development of strategies to improve the resilience of agriculture.

In response to low N fertilizer use efficiency and associated N losses and, climate change-related events, such as drought and disease infestation, novel fertilizers and fertilization strategies are being designed in order to mitigate N losses necessary for reducing N_2O and NO emissions, NO_3 leaching or runoff to water bodies, and the effects of abiotic and biotic stressors on plants (Servin et al., 2015; Angle et al., 2017). The extent of N fertilizer involvement in climate change depends to a large degree on the type of N. However, fertilization using even the most basic N fertilizer, namely urea, together with secondary and/or micronutrient supplementation, can also play a role in enhancing N uptake and mitigating N loss. In addition, micronutrients function in mitigating the impact of abiotic and biotic stressors in plants (Dimkpa and Bindraban, 2016; Elmer and White, 2016). As illustrated in Figure 1, the choice of appropriate N fertilizer and its mode, timing, and rate of application contribute to enhance crop resilience to climate change by reducing N loss. Figure 1 also highlights two technical approaches to improving N fertilizer efficiency: producing intrinsically efficient N fertilizer products and balancing crop nutrition to stimulate the use of N. Here, although the choice of an approach is directly related to its ability to modulate N uptake efficiency to reduce losses, other significant agronomic benefits accrue, as already noted, due to balancing the nutrition in fertilizer formulations (Dimkpa and Bindraban, 2016). That said, obvious increases in the purchase price of improved efficiency fertilizers versus basic fertilizers may be counteracted by using lower rates of the former and by the difference in yields obtained, not to mention the reduction in societal costs associated with negative environmental effects of fertilizers. While each of these individual fertilization approaches has demonstrated applicability for enhancing N use efficiency and/or mitigating abiotic and biotic stressors (Dimkpa and Bindraban, 2016; Angle et al., 2017), integrating them into a systems approach is likely to allow for better maximization of the benefits. Below the ramifications of fertilizer improvement strategies are discussed in more detail, together with evidence of their impact on N use efficiency and abiotic and biotic stress mitigation in rice. Although not possible with rice, examples with other grain crops are provided.

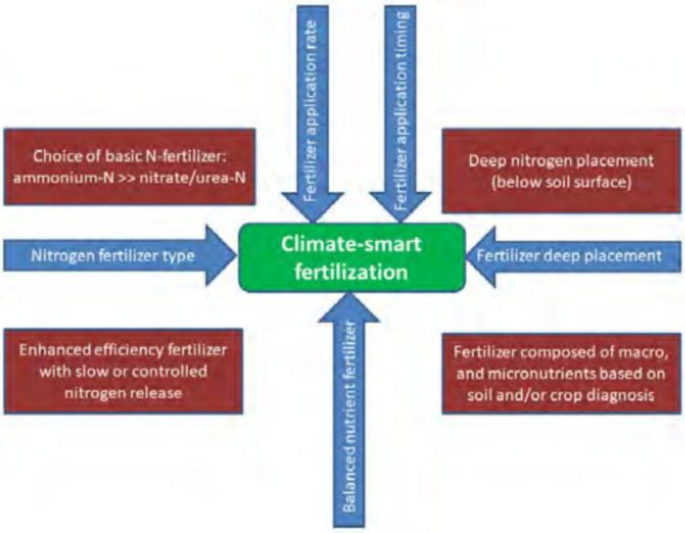

Figure 1. Strategies for maximizing the ecological benefits of fertilizers based on choice, application method, use of improved N fertilizers, and balanced nutrient composition of fertilizers.

3. Adapting Nitrogen Fertilizers for Agricultural Resilience to Climate Change

3.1 Nitrogen Fertilizer Management

Nitrogen loss to the atmosphere from mineral N fertilizers occurs at different degrees, dependent on fertilizer type. A meta-analysis indicated that the greatest N loss is from urea-based N fertilizer, with losses between 10% and 64% (average 18%) from NH_3 volatilization (Pan et al., 2016) and up to 28% from N_2O emission (Wang et al., 2016), dependent on N application rate. Based on comparative N_2O emission studies, Rashti et al. (2015) concluded that substituting urea with nitrate could reduce N loss significantly in upland cropping systems. In contrast, N loss from NH_4^+-based N fertilizers is relatively lower than from NO_3^--based fertilizers; NH_4^+ can be rapidly bound up in soil upon fertilizer application and only later converted to NO_3^- by nitrifying bacteria. In contrast, NO_3^- is prone to rapid denitrification or leaching, contributing much more quickly to the pool of N volatilized, leached, or lost through surface water runoff. Thus, the choice of N fertilizer can play a significant role in the contribution of fertilizers to GHG production. However, where N fertilizer choices are limited, the most available N fertilizer, typically urea, can be managed for improved efficiency by placement strategies. Several IFDC studies on subsurface placement of urea (urea deep placement; UDP) have demonstrated that urea savings of 25-44% are possible, relative to recommended broadcast application of urea in lowland rice, due to negligible NH_3 volatilization loss (Savant and Stangel, 1990; Kapoor et al., 2008; Bandaogo et al., 2015; Gaihre et al., 2015; Huda et al., 2016; Islam et al., 2016; Miah et al., 2016). Notably, although NH_3 is not a GHG, its loss to the atmosphere directly contributes a major reactive N that potentially pollutes the atmosphere. Moreover, NH_3 can subsequently be converted to NO and N_2O, which are GHGs.

Although N fertilizer management practices, such as using the right rates, right application method (e.g., deep placement versus surface broadcasting), or simply preferring one type of N fertilizer over another (e.g., non-urea vs. urea), already can mitigate some of the environmental problems associated with fertilizers (Pan et al., 2016; Angle et al., 2017), it is also clear that improving existing N fertilizer products represents an important step in redirecting fertilizer's role in climate change (Angle et al., 2017). The contribution of improved N fertilizers in mitigating climate change can be evaluated by how much less GHG they contribute to the environment by lowering N_2O and NO emissions and by how much GHG (CO_2) they cause plants to remove from the atmosphere through improving shoot growth for more carbon capture, relative to existing unimproved N fertilizers. For instance, by using several controlled-release N fertilizers, N_2O/NO emission reductions of 13-68% are attainable, compared to urea, dependent on the individual controlled-release technology (Angle et al., 2017). Similarly, photosynthetic rates, and hence, CO_2 removal, could be enhanced by more than 50% of the rate by regular N fertilizer using controlled-release products (Zhao et al., 2013).

3.2 Improved Efficiency N Fertilizers

To better synchronize N availability with crop N demand and reduce N loss, controlled- or slow-release N fertilizers have been produced (e.g., Chien et al., 2009; Timilsena et al., 2014; Ruijter and Corré, 2015). Such improvements essentially involve modifications using chemical, biological, and nanotechnological approaches to coat or encapsulate N with slow-release agents. The functioning of slow-release fertilizers involves two general mechanisms. First is regulating the rate of urea hydrolysis by urease, which reduces the rate of NH_4^+ formation. During the process, loss of N as NH_3 and N_2O is controlled. Second is the reduction of nitrification of NH_4^+ to NO_3, during which N_2O emission and NO_3 leaching and/or runoff rates are controlled. Thus, the aim of both mechanisms, ultimately, is to keep N in the soil much longer as NH_4^+ for synchronized and enhanced uptake by crops (Figure 2).

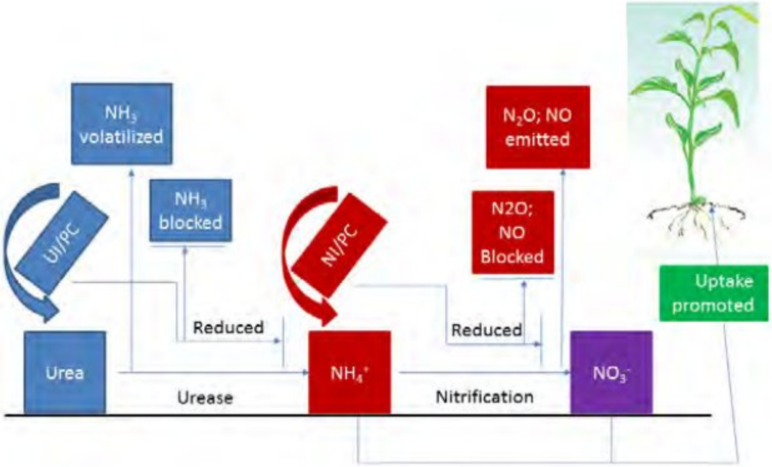

Figure 2. Simplified schematic of pathways for N transformation and losses, with N source as urea or ammonium. The introduction of urease inhibitor (UI), polymer coatings (PC), or nitrification inhibitors (NI) reduce N transformation rates, and thus losses, at each point. Reduction in N loss implies increased N uptake by plants. Losses via nitrate leaching or runoff are not indicated.

To these ends, urease inhibitors, polymers, and/or chemical nitrification inhibitors are being used. With urea-based fertilizers requiring conversion by urease to NH_4^+, chemical urease inhibitors (e.g., N-[n-Butyl] thiophosphoric triamide [NBPT], phenylphosphorodiamidate [PPD/PPDA], hydroquinone) are added to slow urease activity, thereby reducing NH_4^+ production and, thus, loss of NH_3. With NH_4^+-based fertilizers, nitrification inhibitors, including nitrapyrin, dicyandiamide, 3, 4-dimethylpyrazol phosphate (DMPP), and thiosulfate, are blended with the fertilizer to reduce the nitrification rate and associated N_2O, NO, and NO_3^- losses. Alternatively, these fertilizers could be coated with polymers of either chemical or biological origin that permit diffusion through their semi-permeable or impermeable membranes, thereby controlling the release of N at rates that vary with polymer composition, polymer thickness, temperature, and soil moisture level. Examples of commonly used polymers or coating agents include dicyandiamide, polyolefin, aldehydes (e.g., formaldehyde), humic acid, zinc oxide, sulfur, polyurethane, lignin, neem, gum arabic, and starch (Abalos et al., 2014; Azeem et al., 2014). Studies by IFDC on rice using different improved efficiency N fertilizers show that high N loss via NH_3 volatilization from conventional urea can be mitigated by using improved efficiency N fertilizers (Figure 3). Notably, by lowering N transformation rates, improved efficiency N fertilizers are able to both reduce N loss to the atmosphere and its runoff loss in soil. Hence, compared to urea (check treatment), more NO_3 is retained in the soil by improved fertilizers (Figure 4). Accordingly, N application rates for crop production could be reduced without compromising yield (Kottegoda et al., 2017; Zhou et al., 2017).

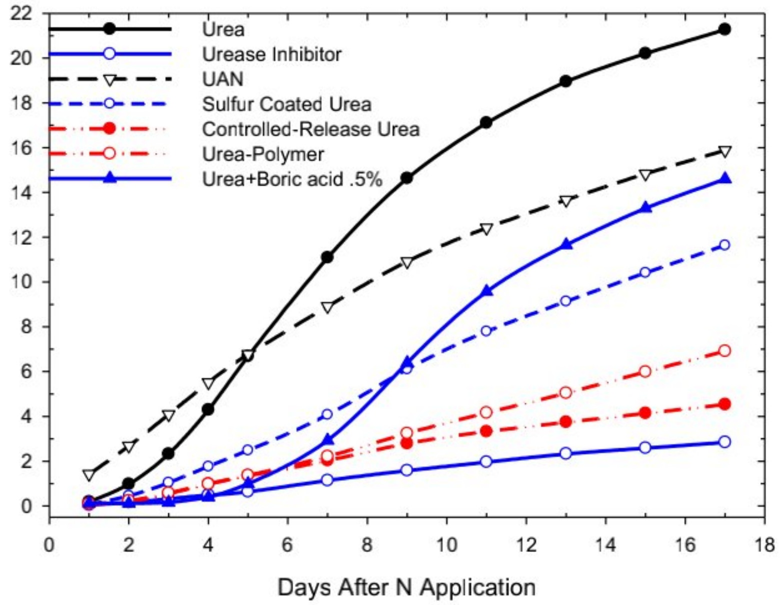

Figure 3. Temporal volatilization of NH_3 during rice growth from conventional urea fertilizer and its mitigation by improved N fertilizer products. UAN: urea ammonium nitrate.

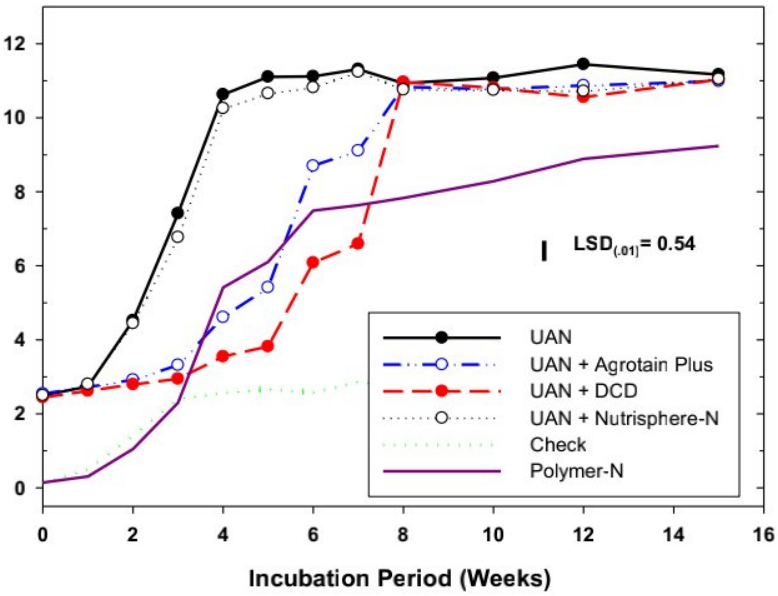

Figure 4. Effect of enhanced efficiency fertilizers on soil nitrate content. UAN: urea ammonium nitrate.

Whereas use of urease inhibitors, nitrification inhibitors, bulk polymer coatings, or sulfur has become standard practice for improving N fertilizers, use of nanotechnology, the design and production of materials at the nano-scale (1-100 nanometer dimensions), has more recently started to emerge in fertilizer development. Here, nanofilms, nanopolymers, or nano-scale additives of other nutrients, such as zinc and phosphorus, are used to modify N fertilizers to slow the release of N. Several studies report these "nanofertilizers" of N as being better able to control urea hydrolysis, and to increase crop yield and N use efficiency, than their conventional counterparts (Dimkpa and Bindraban, 2017; Kottegoda et al., 2017; Zhou et al., 2017). Dependent on the type of nano formulation, controlled N release could result in up to 35% less N release and an 86% reduction in N_2O emission. In some case, these findings are accompanied by significant crop N uptake and yield improvements (Kottegoda et al., 2011, 2017; Pereira et al., 2015; Kundu et al., 2016; Zhou et al., 2017). Notably, Kottegoda et al. (2017) demonstrated in rice that such effects are possible with up to 50% less N fertilizer application using nanohydroxyapatite-improved urea ("nano-urea") compared to conventional urea granules (Figure 5). Similarly, Zhou et al. (2017) reported N fertilizer improvement by formulating nanoclay, sodium humate (a urease inhibitor), and urea. They demonstrated strong reduction in urea hydrolysis and improvement in rice productivity by the nano-urea (Figure 6), wherein a grain yield increase of 11% was realized using 20% less fertilizer, compared to conventional urea. In addition to permitting less introduction of new reactive N into the agricultural system, these findings suggest cost-saving benefits on initial fertilizer investments using nanotechnology, contingent upon accounting for the cost of nano-enabling the urea, compared to other non-nanotechnology-based improvement methods. Unfortunately, many of the studies reporting N use improvement by means of nanotechnology have a major flaw, which the effects were compared with ordinary urea in most cases, instead of urea or other N fertilizers improved by methods other than nanotechnology.

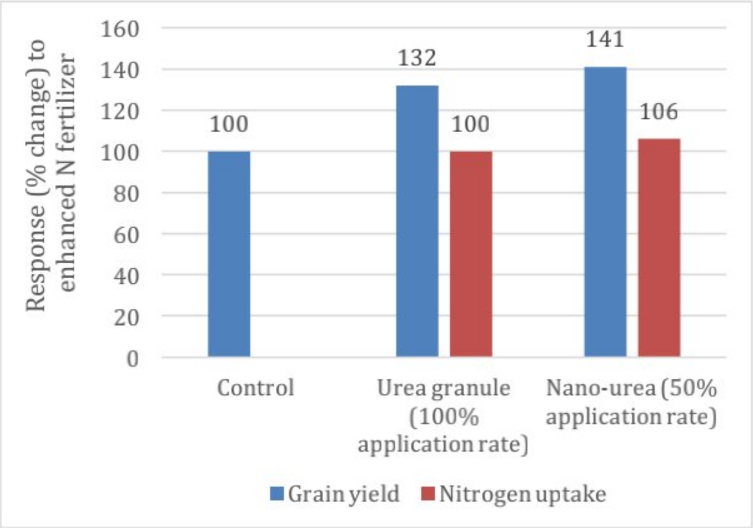

Figure 5. Effect of improved urea (nano-urea) on rice grain yield and N uptake. Nitrogen uptake comparisons are between urea and nano-urea only. Data are modified from Kottegoda et al. (2017) with permission.

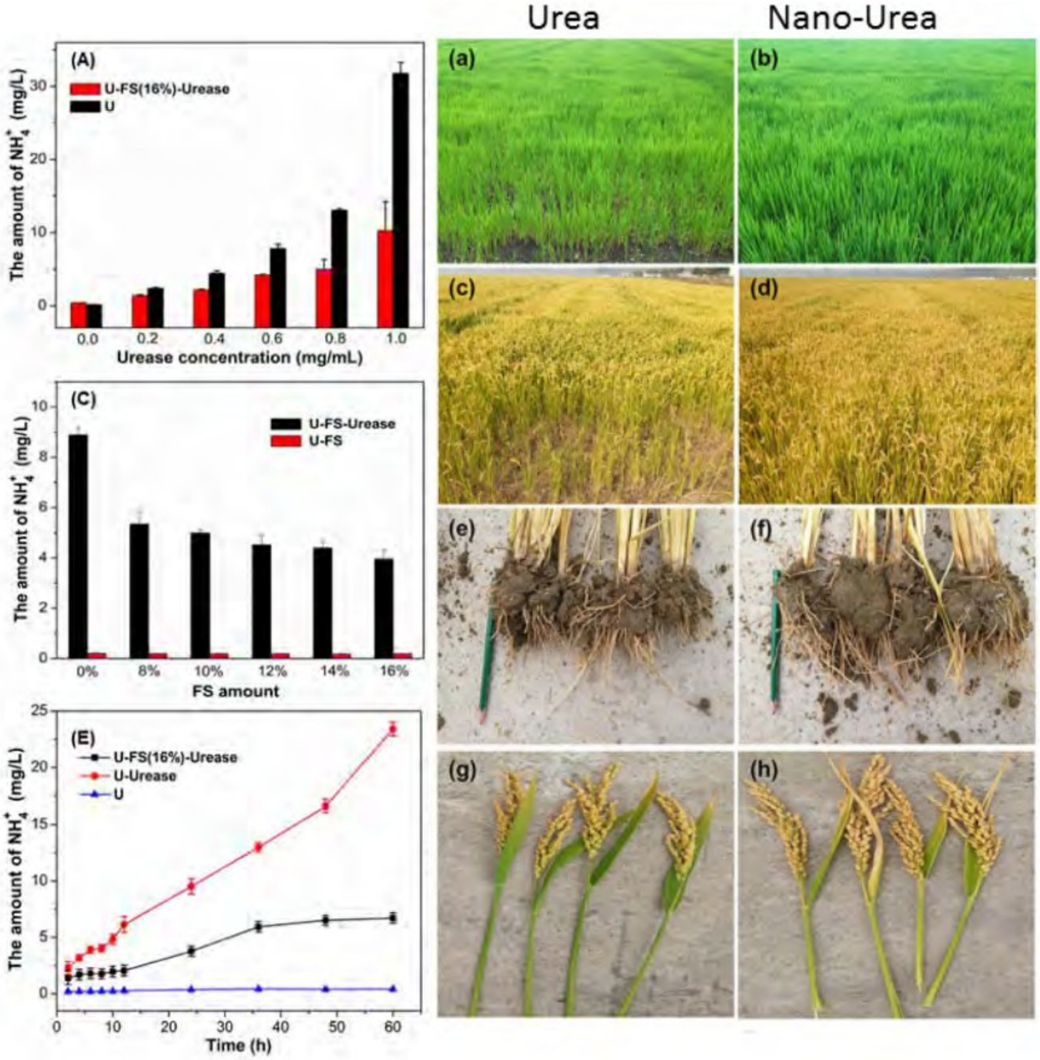

Figure 6. **Effects of "nano" on ammonium production by urea hydrolysis and rice performance under urea fertilization. Left panel (upper row) shows reduction of urea hydrolysis rate in nano urea (red bar) compared to conventional urea (black bar) as a function of urease concentration; middle row shows reduction of urea hydrolysis rate in nano urea with (black bar) and without (red bar) urease treatment, as a function of "nano" concentration; and lower row shows the time course of the reduction of urea hydrolysis in nano urea (black line) and conventional urea, each in the presence of urease, and compared with conventional urea without urease treatment. Middle and right panels are photographic images of field-grown rice plants treated with urea (middle panel) or nano-urea (right panel). Vegetative, root, and ear developments are shown in the upper, middle, and lower rows, respectively. These data culminated in an 11% grain yield increase by using nano-urea (see Zhou et al. [2017] for more detail).**

3.3 Role of Sulfur in Promoting N Use and Mitigating N Losses

The role of sulfur as a nutrient in fertilizers for stimulating crop production is well studied. Sulfur, once converted to sulfate, adds to the completeness of crop nutrition, with the potential to enhance biomass production, as consistently demonstrated in IFDC's work in East Africa for different soils and crops. However, S is also relevant for mitigating fertilizer-induced environmental pollution. The previous section indicates that S is used as a coating agent to improve urea fertilizers by slowing N release. Beginning with the work of Billings et al. (1967) at the Tennessee Valley Authority about half a century ago, IFDC and others have been using S as a coating material for urea improvement. Mechanistically, S forms an impermeable layer over urea that slowly decomposes as a result of microbial, chemical, and physical processes. As shown in Figure 3, the use of S coating in urea can reduce NH_3 volatilization loss by as much as 45%, 18 days after fertilizer application. Similarly, Khariri et al. (2016) reported a lowering (by 15%) of N_2O emission in rice soils by S-coated urea, compared to uncoated urea. With respect to effects on plant performance, a rice yield increase of 10% was obtained upon treatment with S-coated urea, compared to uncoated urea (Kiran et al., 2010). Likewise, Shivay et al. (2016) reports 12% more rice grain yield by S-coated urea compared to uncoated urea, concomitant with N uptake increase of 21% by the plant. In another grain crop, S-coating induced significant lowering of N_2O emission compared to uncoated urea and resulted in significantly more shoot and root biomass production in maize (Dheri et al., 2015). This dual benefit can be viewed in terms of S simultaneously contributing to lowering two GHGs: reducing N_2O emission and permitting more CO_2 capture by plant, thereby increasing plant growth. In wheat, sulfur-induced N recovery of up to 70% from soil under high N treatment with otherwise greater potential for losses has also been noted (Salvagiotti et al., 2009).

4. Micronutrient Fortification for Climate-Resilient Crop Production

The second fertilizer improvement strategy to be addressed in this paper concerns the balancing of nutrients in fertilizer products. This has serious ramifications other than just improving N use because of its role in engendering crop resilience to climate-induced abiotic and biotic stressors and its benefits for crop and human nutrition. Ample evidence demonstrates that the inclusion of micronutrients in N(PK) fertilizers can markedly increase the resilience of plants to climate change effects, such as drought, salinity, and disease. Notably, even in the absence of environmental stressors, these nutrients are known to enhance crop performance, productivity, and nutritional quality, regardless of the N status of the soil (Dimkpa and Bindraban, 2016). Prominent among the micronutrients in this regard are Zn, Cu, and B and, to a lesser extent, Fe and Mn. Despite the benefits, these micronutrients are hardly included in the national fertilizer recommendations in many countries, including Myanmar. In particular, the need for Zn inclusion in fertilizers is warranted by the fact that Zn deficiency is a growing global human health problem that agronomic fertilization has the potential to address. Notably, Myanmar has been identified as one of the countries with a high population percentage having low Zn dietary intake (Wessells and Brown, 2012).

Regarding their role under abiotic stress, micronutrients mitigate drought effects in plants by several mechanisms, including increasing water use efficiency, maintaining membrane stability which otherwise causes tissue flaccidity by drought-induced wilting, and detoxifying toxic free radicals that accumulate in plants during water scarcity. All of these actions are related to micronutrients' multiple roles in stimulating several enzymes and plant processes related to abiotic stressors, water interactions, or nutrient uptake (Karim and Rahman, 2015; Dimkpa and Bindraban, 2016). For example, Zn activates enzymes that regulate plant response to water stress, and both Cu and B are involved in cell wall strengthening and functioning. Notably, under drought stress, plants produce increased quantities of abscisic acid (ABA) to optimize stomatal closure and conserve scarce water. Interestingly, Zn fertilization has been shown to increase ABA production in plants (Zengin, 2006); hence, it is a potential strategy for fertilizer induction of tolerance to drought stress in plants.

Conversely, micronutrients such as Zn and Fe modulate salinity effects on plants by reducing osmosis-induced Na accumulation. This is possibly due to competition for binding sites at the cellular interface between Na and metallic micronutrients. Concomitant with that is the enhancement of K uptake relative to Na, and the regulation of antioxidative enzymes and metabolites ostensibly protecting the plant from salinity stress (Soliman et al., 2015; Saeidnejad et al., 2016). Mechanistically, increased K uptake facilitates osmotic pressure, drawing water into the plant to dilute excess Na effects. As such, K fertilization could be an appropriate strategy in rice production systems (Zain et al., 2014), especially where alternate wetting and drying is practiced, whereby plants may become exposed to elevated salt levels due to precipitation during the drying regime. As demonstrated below, the above-discussed cellular-level effects of micronutrients under drought or salinity stress often translate to agronomic and nutritional benefits in different crops. Therefore, micronutrients have strong promise in climate-sensitive agriculture as smart fertilizers for facilitating quality crop production in drought- and salinity-prone agroecosystems and could prove immensely beneficial for countries such as Myanmar, given its history of drought and salinity and the need for agricultural resilience against diseases.

4.1 Micronutrients Impact under Drought Stress

Crop trials involving different species have consistently shown micronutrient fertilization as capable of increasing drought tolerance (reviewed by Karim and Rahman, 2015). Conversely, drought-induced reduction in grain yield also is more pronounced with micronutrient deficiency, especially Zn (Dimkpa et al., 2017). Although studies conducted specifically in rice systems for drought evaluation of micronutrients appear to be scarce, fertilization of drought-stressed plants with micronutrients has led to significant mitigation of drought effects on vegetative and reproductive development in other crops. For instance, under drought, average wheat grain yield decreased by 25%; however, the addition of Zn increased wheat yield by 16%, thus lowering the loss in yield due to water shortage from 25% to 13% (Bagci et al., 2007). Similarly, Karim et al. (2012) demonstrated application of Zn, B, and Mn under drought stress to increase wheat grain yield by 15%, 19% and 13% concomitantly with increased grain accumulation of Zn (29%), B (17%), and Mn (52%), respectively, relative to untreated plants. In other studies, yield of wheat was reduced 30% by drought but was improved by between 13% and 18% upon B application, dependent on application time (Abdel-Motagally and El-Zohri, 2016).

IFDC's recent studies have contributed to unraveling the influence of micronutrients on crop yield and N uptake under drought and non-drought conditions alike. For example, drought stress reduced biomass production, grain yield, and N uptake in soybean to 48%, 47%, and 52%, respectively (Dimkpa et al., 2017). However, under drought stress, a micronutrient formulation of Zn, B, and Cu administered to plants as oxide or salt mitigated the effect of drought by enhancing biomass production, grain yield, and N uptake, relative to drought-stressed plants not exposed to the formulation (Figure 7).

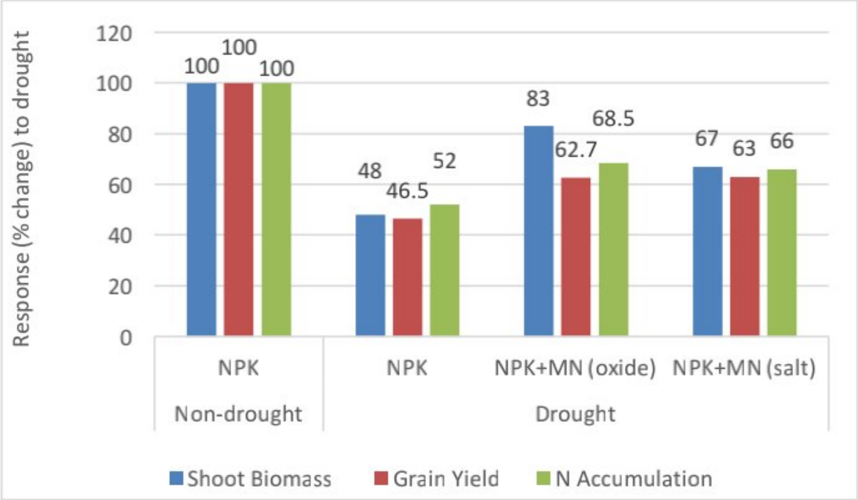

Figure 7. Response of soybean under drought stress to a micronutrient (MN) formulation of Zn, B, and Cu as oxide powders or salts. Data are modified from Dimkpa et al. (2017).

Under non-drought condition, Zn application raised rice grain yield, grain Zn, and shoot N contents by 8%, 18%, and 8%, respectively, in flooded growth condition (Ranjha et al., 2001). Similarly, rice growth, grain production, N accumulation, and soil N retention were improved 13-25%, 19-34%, 34-39%, and 25-36%, respectively, upon Zn fertilization using different methods, including soil and foliar (Ghoneim, 2016). Viewed from a nitrogen management perspective, these findings suggest Zn as capable of both increasing the accumulation of N in plants and leaving residual N in soil in a more stable form, thereby potentially reducing N losses.

4.2 Micronutrients Impact under Salinity Stress

As noted, salinity in rice production systems is of concern in Myanmar; more than 27,000 ha of the total land used for rice farming is salinity prone (RSDS, 2015), which is likely to increase, as previously indicated. Notably, fertilization of salinity-stressed crops with different micronutrients has been shown to alleviate salinity-induced loss in productivity. For example, treatment with B or Zn decreased Na and Cl uptake but increased K uptake in rice challenged by salinity stress. This resulted in improved vegetative growth and paddy yield increases of between of 80% and 163% over the control for B and between 41% and 56% for Zn, compared to the controls, across different cultivars or micronutrient treatment rates (Mehmood et al., 2009; Ashraf et al., 2014). Likewise, rice response under salt stress was improved by Zn application, generating significant increases in grain yield and K uptake, while depressing Na and Cl uptake (Jan et al., 2016).

4.3 Micronutrients Impact under Biotic Stress

Rising temperatures and changes in rainfall pattern are among climate change indicators influencing the development of plant pest and disease epidemics. In Myanmar, insect pest incidences are generally low. However, due to abnormally high rainfall, it is likely that insect pest prevalence will increase, as found in 2002 for rice ball midge. In the case of rice diseases, incidences are more widespread in Myanmar. Dependent on the disease agent and year, incidences ranged between <5% and 65% (Naing et al., 2008). Notably, fertilization of rice with certain nutrients helps to control pests due to their effect on modulating sugar and amino acid production, increasing the production of allelochemicals, and thickening cell walls, which retards stem borers (IRRI, downloaded August 2017) Similarly, balanced crop nutrition plays a role in plant disease tolerance. Although studies that have directly assessed the role of nutrition in suppressing diseases under "climate-change" conditions are lacking, rice disease-causing pathogens have been shown to be controllable by nutrition-based treatment strategies (Rodrigues and Datnoff, 2005). Mechanistically, Zn activates signals for the cellular activities of proteins involved in disease resistance in cereals (Shirasu et al., 1999), and Zn-efficient cereal crop varieties are known to be more resistant to plant disease than Zn-inefficient varieties (Grewal et al., 1996). Copper is a cofactor for important proteins, including plastocyanins, peroxidases, and multi-Cu oxidases, which are involved in plant response to pathogenic infections (Evans et al., 2007). Studies have found some of these enzymes, as well as pathogenesis-related protein genes, to be activated by Cu application under pathogen attack (Elmer et al., 2017). However, other micronutrients, including Zn, Mn, and B, have also shown ability to suppress plant diseases (Servin et al., 2015; Elmer and White, 2016; Elmer et al., 2017). Interestingly, these micronutrients not only directly inhibit pathogen growth, but also engender considerable systemic resistance in the plant against upcoming diseases. Diseases affecting eggplant, watermelon, tomato, and other crops have been systemically controlled or mitigated using micronutrients, leading to substantial increases in crop yields (Servin et al., 2015; Elmer and White, 2016; Elmer et al., 2017). Notably, micronutrient effects on diseases seem to be more effective with early exposure to the micronutrients, prior to disease onset (Imada et al., 2016; Elmer et al., 2017). These findings clearly highlight the importance of a disease treatment window with nutrition, which may be relevant for the seasonal cultivation of rice in Myanmar. The literature on this subject indicates that a balanced nutrition fertilization regimen can be pursued both for decimating pathogen populations and for priming crops, as it were, for future resistance to pathogen attack. Elmer et al. (2017) discusses how sufficient Cu availability could induce host defenses that then prevent or minimize infection, delay the onset of symptoms, and reduce the severity of disease when they do establish. Particularly for rice, high N application increases susceptibility to pests and diseases (IRRI, 2015; Mukherjee et al., 2005). Thus, it is possible that lowering N application rate and offsetting with a suite of yield-enhancing and disease-preventing micronutrients may help with the control of diseases while allowing for uptake of sufficient N even at low application rates. Alternatively, fertilizing the plants with such micronutrients before a second split N application may help with priming the crop against susceptibility that may be induced by the additional N or by climatic factors, such as drought.

5. Perspectives

In comparison with other South Asian farmers, Myanmar farmers have a lower adaptive capacity to confront the high impacts of climate change (SeinnSeinn et al., 2015). Hence, they are in need of strategies to sustain production in the face of climate change events associated with the region. While fertilizer misuse – under- and overuse – has serious consequences in agro-environmental systems, appropriate use of fertilizers is one strategy that can be applied to sustain production. Data from studies on improved N agronomic management, use of improved N-fertilizers, and balanced crop nutrition all demonstrate enhanced use efficiency of N, with potential to mitigate both GHG emissions and the adverse abiotic and biotic challenges brought about by climate change. Thus, for countries such as Myanmar, the above-described positive impacts of fertilization will be favorable for addressing multiple climate change-related challenges, such as drought, salinity, and pest and disease. Moreover, increased CO_2 as a result of climate change is reported to lower the nutrient quality of crops including rice (Loladze, 2014; Myers et al., 2014; Nakandalage et al., 2016), which could pose a serious human health threat for the predominantly rice-consuming population, in addition to weakening the physiological ability to thrive under a changing climate. These warrant deliberate strategies of developing improved N fertilizers capable of enhancing N use efficiency, which in turn contributes to increased biomass production and lowering of CO_2 levels, and promoting balanced fertilization in order to harness the power of micronutrients in enhancing N use efficiency and to replenish diminished nutrients, both for crop adaptation and human health improvement. Quite surprisingly, although drought is a potentially major challenge limiting rice production, there is a notable lack of research demonstrating the alleviating effects of micronutrients on this crop under drought stress. Therefore, a range of studies to evaluate the impacts of different micronutrients and their mixtures, as well as different application methods, including soil and foliar, on rice growing under drought challenge should be conducted. Obviously, for Myanmar, where at least 15% of the land devoted to rice production is affected by drought, the significance of a strategic micronutrient fertilization regime to mitigate the effects of drought cannot be overstated. A recent article on new fertilizers suggests that Myanmar is already pursuing the inclusion of nutrients other than NPK in the national fertilizer recommendations (Dimkpa and Bindraban, 2017). Several products are reported to be under consideration as new fertilizers that include nutrients advantageous for enhancing crop N use and improving the nutritional quality of crop produce in the face of climate change threats to the environment and humans.

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