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**The Biophysical Potential for Urea Deep Placement
Technology in Lowland Rice Production Systems of
Ghana and Senegal**

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Contents

Abstract	v
Acknowledgments	vi
1. Introduction	1
2. Materials and Methods	3
3. Results	5
4. Discussion	10
References	12

Tables

2.1 Biophysical suitability of urea deep placement in rice	3
3.1 Regional estimates of current rice production and area of biophysical suitability for urea deep placement in Ghana and Senegal	7

Figures

3.1 Biophysical suitability maps for urea deep placement for Bangladesh, Ghana, and Senegal overlaid with rice yields derived from SPAM	5
3.2 Comparison between the SPAM yields and DSSAT-simulated yields of 1999–2001	7
3.3 Yield increase in Ghana due to current rate of N as UDP and doubling current rate of N as UPD	9
3.4 Yield increase in Senegal due to current rate of N as UDP and doubling current rate of N as UPD	9

ABSTRACT

The application of nitrogen (N) fertilizers is still insufficient across cropping systems in Africa south of the Sahara, while plant uptake of nitrogen is often inefficient and wasteful even when farmers apply fertilizers. This leaves sizable room for improving the productivity of crops and managing nutrient cycles. Fertilizer deep placement is a technology designed to enhance the efficiency of nutrient delivery to crops by placing granulated fertilizer directly in the root zone. Deep placement maximizes nutrient uptake by crops while using less fertilizer than surface broadcasting, and minimizes N losses due to runoff and ammonia volatilization. Urea deep placement (UDP) technology has been widely adopted in lowland paddy rice production systems in South Asia, especially in Bangladesh. There is a growing interest to scale up UDP adoption in West African countries, such as Ghana and Senegal, but a limited number of studies have been published from the region to support developing strategies. To contribute to the evidence-base, we use a grid-based cropping systems modeling framework, combined with analyses on the characterization of UDP and its geospatial targeting, and map the extent of biophysical suitability for UDP across regions in Ghana and Senegal and estimate potential yield increases under this technology. Results show that 77, 39, and 23 percent of the current rice growing areas in Bangladesh, Ghana, and Senegal, respectively, are biophysically suitable (based primarily on soil characteristics) for UDP technology. The area of suitability appears aggregated across the extent of the rice growing area in Bangladesh, whereas the areas in Ghana and Senegal have a patchier, less-connected spatial distribution, possibly hindering the pathways of distribution and adoption of technology and equipment at scale. Across regions in Ghana simulated increases in rice yields under UDP ranged from 2 to 10 percent under the current (low) rate of N fertilization. Simulated yields more than doubled under a doubled (intensified) rate of N. Much higher yield increases were estimated across regions in Senegal (10 to 76 percent) since baseline yields in this country are generally lower than those in Ghana. Overall, the potential to scale UDP in Ghana and Senegal, and presumably in other West African countries, may be more limited compared with Bangladesh due to the nature of the soils. Therefore, in addition to UDP a variety of interventions are currently needed to improve the production of lowland rice cropping systems and manage nutrients in Ghana and Senegal, especially where soils are not suitable for UDP.

Keywords: urea deep placement (UDP); potential yield; Decision Support System for Agrotechnology Transfer (DSSAT); lowland rice; biophysical suitability; Africa south of the Sahara

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1. INTRODUCTION

Poor management of nitrogen (N) on the world's croplands is an agronomic challenge for producers with potential consequences for human health and food security, has led to widespread nutrient pollution and the degradation of water quality and aquatic ecosystems, and contributes to climate change through the emission of nitrous oxide from fertilized fields (Foley et al. 2011). Nutrient overloads (N in particular) in more economically developed regions such as the United States, western Europe, China, and northern India have accelerated environmental problems (Foley et al. 2011), while insufficient nutrients in poorer regions of the world, such as Africa south of the Sahara (SSA), have failed to sustain soil fertility and increase production by supplementing nutrients to already degraded soils (Foley et al. 2011; Glover, Reganold, and Cox 2012; Sanchez et al. 1997). These N imbalances need solutions to keep pace with rising global food demands in the coming decades. This is particularly important in underdeveloped regions such as SSA where yield gaps remain chronically large primarily due to poor soils and unequal access to the global share of nutrients (Foley et al. 2011; Mueller et al. 2012). Further gains in crop production in many regions of the world will likely come about through the intensification of agriculture on existing cropland by maximizing ecosystem services and input efficiencies (Foley et al. 2011; Garnett et al. 2013; Pretty, Toulmin, and Williams 2011). As part of this vision, effective practices in N management and innovations in fertilizer application are at the forefront.

The deep placement of fertilizer in the form of urea supergranules is a technology designed to reduce N losses that occur through ammonia volatilization and water runoff, while allocating more available N to crop plants and increasing grain yields. It is especially practiced in the lowland rice cropping systems of South and Southeast Asia with the greatest extent found in Bangladesh (IFDC 2013a, 2013b; Savant and Stangel 1990). In much of these areas, farmers traditionally apply N to rice by broadcasting prilled urea on fields around the time seedlings are transplanted followed by one or more top dressings. Under broadcasting, rice plants get only about 25 to 30 percent of the applied N with much of the rest lost through ammonia volatilization, denitrification, runoff, or leaching (Craswell et al. 1985; Savant, Craswell, and Diamond 1983; Savant and Stangel 1990). Under urea deep placement (UDP), a urea supergranule, or briquette, is hand-buried 7 to 14 centimeters deep between every four rice plants about a week after transplanting. This better synchronizes the delivery of nutrients with the demands of the crop, thereby strengthening nitrogen balances, increasing soil fertility and nitrogen assimilation, and boosting rice yields—all with less fertilizer (IFDC 2013b).

In Bangladesh UDP occupies more than 2 million hectares of farmland across 22 districts and 80 *upazilas*, or about 12 percent of the nation's annual irrigated rice crops (IFDC 2013a; Liverpool-Tasie, Adjognon, and Kuku-Shittu 2014; Roy 2012). Under areas of UDP adoption rice yields have increased (15 percent average, up to 35 percent has been reported), N fertilizer consumption has decreased (about a third less urea is required under UDP), and N losses have also reportedly decreased (up to 50 percent), including decreased emissions of N₂O and NO greenhouse gasses (Choudhury and Kennedy 2005; IFDC 2013a; Mohanty et al. 1998; Savant and Stangel 1990).

In most of the lowland rice growing regions of SSA, however, UDP is still a novel technology. Africa ranks eighth in global paddy rice production with the majority grown in West Africa (IFDC 2013b). The potential of UDP in a panel of SSA countries is currently under investigation by the International Fertilizer Development Center (IFDC) and the United States Agency for International Development (USAID). IFDC has conducted field trials in 13 SSA countries since 2009. Averaged across seven countries (Benin, Burkina Faso, Mali, Niger, Nigeria, Senegal, and Togo), it reported a 30 percent yield increase in UDP rice trials compared with broadcasting, with Burkina Faso, Niger, and Nigeria generating the best results (IFDC 2013b). As part of the USAID-funded program and the New Alliance for Food Security and Nutrition, the Scaling Seeds and Technologies Partnership (SSTP) is currently targeting UDP in Ghana and Senegal as one of several potential technologies for scaling to promote the increase of paddy rice yields and food security in those countries (along with a suite of other outcome indicators).

In any region of the world, the characteristics of soil, climate, and crop management are likely critical determinants for UDP success (Mohanty et al. 1998). UDP is most likely to succeed in rice growing areas that are prone to N losses through surface water runoff and ammonia volatilization rather than denitrification or leaching (Eriksen, Kjeldby, and Nilsen 1985; Mohanty et al. 1998; Rao 1987). At the same time, volatilization is accelerated by high pH and alkalinity, increasing temperature, and drying soil surface (Christianson et al. 1993; Katyal et al. 1985; Schwab and Murdock 2005). Compared with surface placement of urea, ammonium levels in floodwaters are lower under deep placement, thus lowering potential N losses to ammonia volatilization (Craswell et al. 1981; Katyal et al. 1985). The potential of UDP also depends on soils that are structurally appropriate for deep placement of urea and water retention. In clay and silt soils that have a higher capacity to hold water, concentrated N from UDP is released slowly to roots and plants are able to uptake most of the UDP nitrogen as the season progresses (around 60 percent) (Rao 1987; Savant and Stangel 1990). In lighter-textured and sandy soils the high loss of N through leaching will significantly decrease N uptake by rice plants and eventually grain yield too (Mohanty et al. 1998; Savant and Stangel 1990). UDP is not recommended, therefore, in dryer areas with low or infrequent rainfall, acidic soils, and light-textured soils where percolation rates may exceed 5 millimeters per day, particularly if the soil is low in organic matter and cation-exchange capacity (< 10 milliequivalents per 100 grams of soil) (Buresh 1987; Katyal et al. 1985; Mohanty et al. 1998; Savant and Stangel 1990; Vlek, Byrnes, and Craswell 1980). Using these biophysical criteria, we can map the spatially explicit suitability of UDP anywhere.

In this study we demonstrate a decision support strategy for SSTP by quantifying the potential geospatially explicit impacts of UDP on lowland rice cropping systems in Ghana and Senegal. For each country we first mapped the biophysical suitability of UDP within the rice growing regions based primarily on soil attributes at a fine spatial resolution (5 arc-minute, or 10 kilometers), then used a process-based model to predict the potential yield change in each pixel in response to UDP. Results were aggregated at the national and regional levels. We prepared a similar map for Bangladesh to compare biophysical suitability between the two distinct geographies (Southeast Asia and West Africa) as a predictor of what we can expect in terms of scale in Ghana and Senegal, relative to where it has had the most success.

2. MATERIALS AND METHODS

Mapping the Geography of Biophysical Suitability

To map the geography of suitable areas for UDP in rice growing regions of Ghana, Senegal, and Bangladesh, we retrieved the site-specific soil properties of texture classes and pH of topsoil (0 to 30 centimeters) from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012) and filtered for two criteria: (1) excluding sandy loam, loamy sand, and sandy-textured soils; and (2) excluding acidic soils with pH less than 5.2 (Table 2.1). The literature on the criteria of other biophysical factors for the performance of UDP, such as rainfall pattern, was limited; hence, they were not considered in the filtering process.

Table 2.1 Biophysical suitability of urea deep placement in rice

Criteria	Ideal Property	Negative Impact Otherwise
Soil	Medium-high fertility	Low soil fertility can lead to high potential of nitrogen leaching.
	Clayey or silt-textured soils with low permeability	Lighter-textured, silt loam, or sandy soils, with high percolation rates (> 5 millimeters/day) and low cation-exchange capacity (< 10 meq 100 g ⁻¹ soil) can result in high loss of N via leaching and significantly decrease N uptake by rice plants.
	Nonacidic	Acidic soils (< 5.2 to 6.0) are typically lower in cation-exchange capacity and organic matter, both of which are positively correlated with the rate of ammonia volatilization. Even a pH as low as 5.4 can speed the rate of volatilization in flooded soils, although the rate increases with increasing pH. If the potential of N loss to the atmosphere (volatilization) is low under surface applications of N, then the deep placement of urea supergranules may have little impact on plant productivity over broadcasting. Neutral or alkaline soils are more suitable (common with flooded, lowland rice cultivated areas).
Climate	Adequate rainfall	High and frequent rainfall can lead to high potential for N loss from runoff. In areas with such rainfall patterns, surface N application methods can damage the environment. Light or infrequent rainfall can inhibit the timely release of N from the urea supergranules. Overall, rainfall requirements have not been precisely established.

Source: Buresh (1987); Katyal et al. (1985); Mohanty et al. (1998); Savant and Stangel (1990); Viek, Byrnes, and Craswell (1980).

We then overlaid the areas of suitability in each country with current rice-producing areas identified using the results from the Spatial Production Allocation Model (SPAM) by HarvestChoice (You et al. 2014a; 2014b). The SPAM model uses 5 arc-minute grid cells (approximately 10 kilometers by 10 kilometers) to disaggregate subnational crop production statistics and allocate the spatially explicit distribution of important crop production variables pixel by pixel, such as harvested area, yield, and production. For each pixel representing a share of rice production, therefore, biophysical suitability of UDP technology was determined by our model parameters in a binary system (either suitable or not), and we then aggregated total percentage area of suitability at the regional and country levels.

Estimating Potential Impact on Rice Yields

To estimate the potential impact of UDP on rice yields within the areas identified above, we used a process-based rice growth model, CERES-Rice, of DSSAT (Decision Support System for Agrotechnology Transfer; Jones et al. 2003) v4.5.1.23. DSSAT includes a suite of models for simulating crop growth and yield as a function of soil water and nutrient dynamics as well as weather conditions and

farmers' management practices at daily time-step. DSSAT has been widely used as a research tool for exploring changes in crop growth and yield in response to various “what-if” scenarios involving different management practices, climate, and agricultural technologies. Various types of information required to run the DSSAT simulations were transferred from a grid-based database developed by the International Food Policy Research Institute (Rosegrant et al. 2014), including baseline soil, climatic conditions, and representative farming practices at 30 arc-minute grids. Using this information as the baseline, we first calibrated model parameters related to a specific rice cultivar for each country's rice production system under a “business-as-usual” (or baseline) nutrient management method, where the broadcast placement of urea fertilizer was assumed. For this calibration, we ran DSSAT simulations of rice cropping systems in each country with historical daily weather data for the period 1981 to 2010 and compared the simulated rice yields with those estimated from SPAM at each cell. This calibration procedure was expedited by using the SCE-UA (Shuffled Complex Evolution–Universal Algorithm; Duan, Gupta, and Sorooshian 1992) coupled with DSSAT. SCE-UA minimizes an objective function that measures model fit to observations by using a generic algorithm to find optimal parameter values with upper and lower limits as defined by previous experience and literature reviews. After SCE-UA performed with 5,000 iterations, we determined the globally optimum set of parameter values that minimize the root-mean-square error between simulated yields of year 2000 and estimated yields from SPAM 2000. After the calibration process, we ran simulations with UDP application by setting the in-built option for N fertilizer application method of CERES-Rice as [Deep placement of urea supergranules at a depth of 10 centimeters beneath the surface soil] at two N rates for Ghana and Senegal: (1) 20 kilograms of N per hectare per year (current rate; Potter et al. 2010) and (2) 40 kg N ha⁻¹ yr⁻¹ (doubled rate). Gridded results in each country were then aggregated by region.

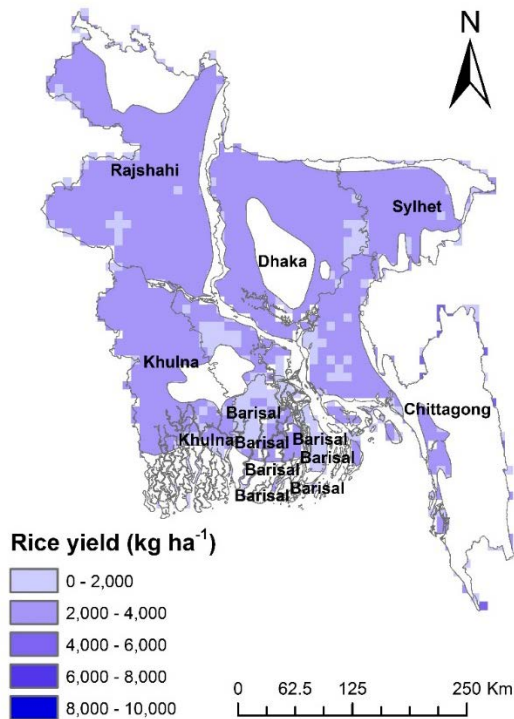
3. RESULTS

Biophysically Suitable Area

The results of mapping biophysical suitability showed that 77, 39, and 23 percent of the current rice-producing areas in Bangladesh, Ghana, and Senegal, respectively, are feasible for UDP technology (Figure 3.1; Table 3.1). The area of suitability appears aggregated throughout the extent of the rice growing area of Bangladesh, whereas the areas in Ghana and Senegal have a patchier, less-connected spatial distribution (Figure 3.1). In the more productive rice growing regions of Ghana—the Northern and Upper East—where more than 30,000 hectares are cropped to rice, more than 40 percent of the area is suitable for UDP technology (Table 3.1). Results from the top rice-producing regions in Senegal were at two extremes: Saint Louis was highly suitable (45 percent of the area), whereas only 10 percent of Ziguinchor was suitable (Table 3.1). Overall, approximately 46,478 and 21,343 hectares of the current area under rice production in Ghana and Senegal, respectively, are estimated to be biophysically suitable for the performance of UDP technology (Table 3.1).

Figure 3.1 Biophysical suitability maps for urea deep placement for Bangladesh, Ghana, and Senegal overlaid with rice yields derived from SPAM

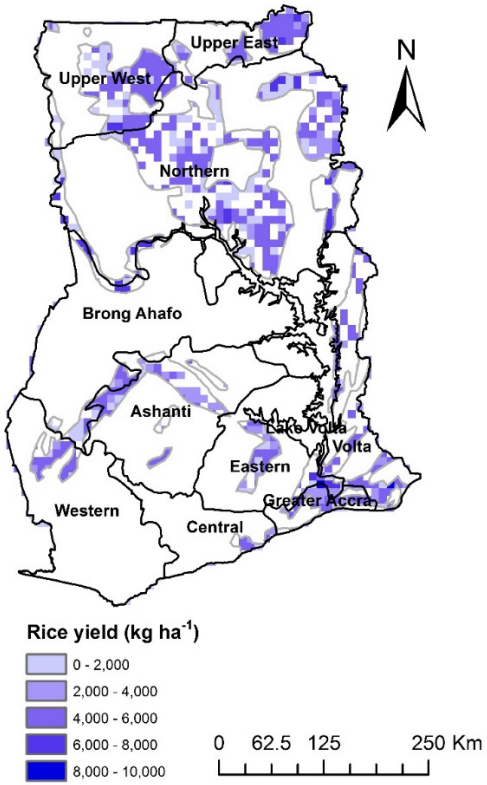
(a) Bangladesh



Source: Authors.

Figure 3.1 Continued

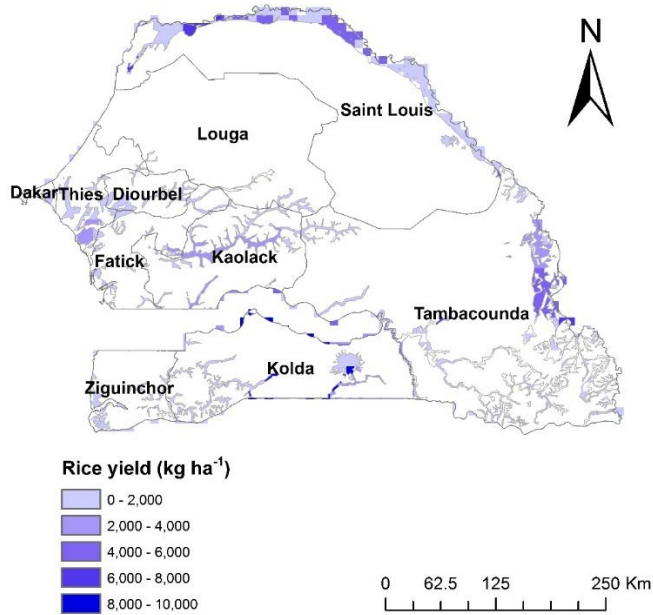
(b) Ghana



Source: Authors.

Figure 3.1 Continued

(c) Senegal



Source: Authors.

Table 3.1 Regional estimates of current rice production and area of biophysical suitability for urea deep placement in Ghana and Senegal

Ghana				Senegal			
Region	Production area (ha)	Suitable area (ha)	Suitable area over production area (percent)	Region	Production area (ha)	Suitable area (ha)	Suitable area over production area (percent)
Ashanti	5,086	315	6	Dakar	51	5	10
Brong Ahafo	4,681	142	3	Diourbel	0	0	0
Central	174	12	7	Fatick	747	131	18
Eastern	13,171	4,902	37	Kaolack	1,188	101	9
Greater Accra	2,717	1,729	64	Kolda	23,271	3,080	13
Lake Volta	280	280	100	Louga	239	0	0
Northern	32,639	13,231	41	Saint Louis	31,418	14,199	45
Upper East	31,322	19,279	62	Tambacounda	3,351	692	21
Upper West	4,145	1,522	37	Thies	285	56	20
Volta	9,504	4,267	45	Ziguinchor	31,005	3,079	10
Western	15,098	783	5				
Sum	118,817	46,462	39	Sum	91,555	21,343	23

Source: Authors.

Yield Potential

Through the calibration procedures where coefficients of rice cultivars in DSSAT were adjusted to optimize the fit between simulated and observed yields, we obtained an R^2 greater than 0.7 in both Ghana and Senegal (Figure 3.2). SPAM yields in Ghana, which were on average 3 metric tons per hectare per year, significantly correlated to simulated yields with a slope close to 1.0. A similar pattern was observed when SPAM yields in Senegal, which were on average 1.2 t ha⁻¹ yr⁻¹, significantly correlated to the simulated yields, although the R^2 was slightly lower (Figure 3.2).

Figure 3.2 Comparison between the SPAM yields and DSSAT-simulated yields of 1999–2001

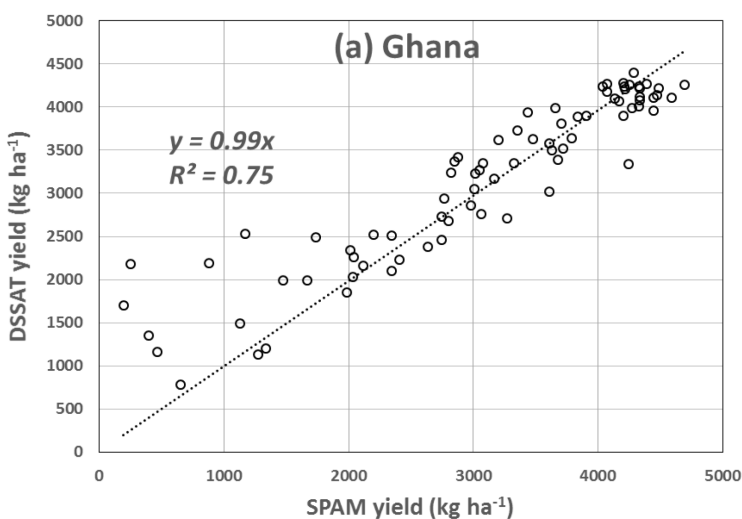
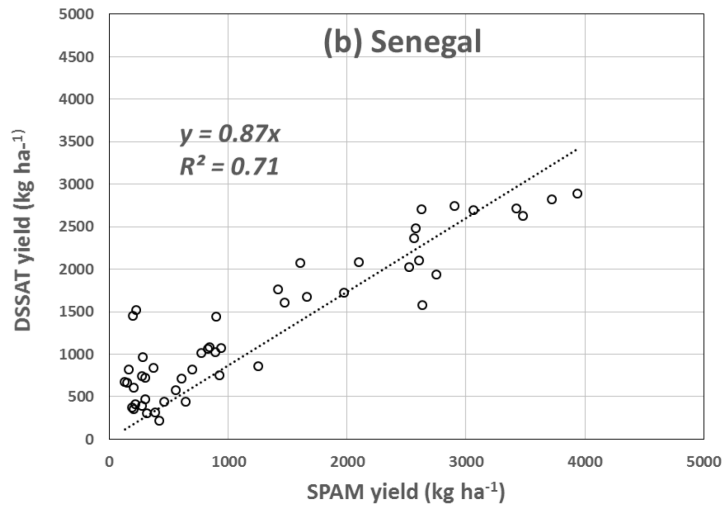


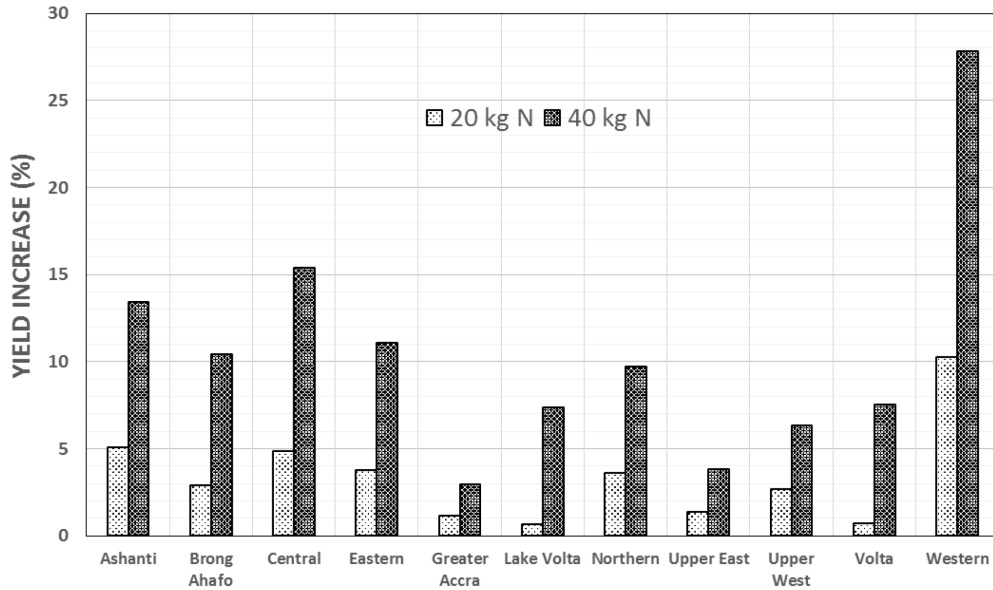
Figure 3.2 Continued



Source: Authors.

By running DSSAT simulations with calibrated model parameters and summarizing the results within the extent of the rice growing area according to SPAM, we estimated how much yield could potentially increase under UDP adoption versus surface applications of N (baseline scenario). In Ghana (Figure 3.3), the potential increases in rice yields ranged from 2 to 10 percent under the current (low) rate of N fertilization (~20 kg N ha⁻¹ yr⁻¹). In the more productive rice growing regions with the greatest potential of UDP in terms of biophysical suitability—the Northern and Upper East (Figure 3.1; Table 3.1)—percentage yield increases were less than 5 percent (Figure 3.3). However, yields more than doubled in each region under the doubled (intensified) rate of N (40 kg N ha⁻¹ yr⁻¹) (Figure 3.3). Although the extent of many of the soils in the Western region of Ghana are mostly unsuitable for UDP technology (Figure 3.1; Table 3.1), rice yields increased by more than 25 percent under UDP adoption at the higher rate of N (Figure 3.3).

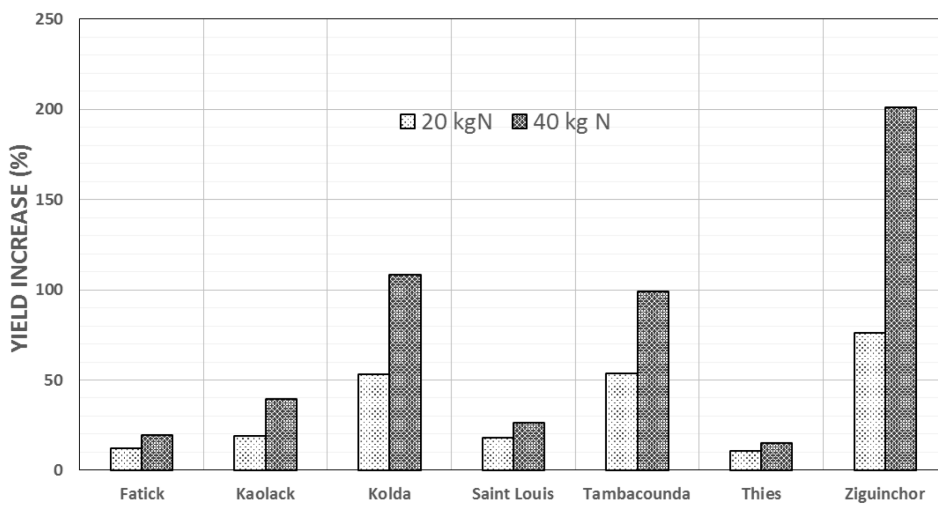
Figure 3.3 Yield increase in Ghana due to current rate of N as UDP and doubling current rate of N as UDP



Source: Authors.

Much higher yield increases were estimated in Senegal (Figure 3.4) where (baseline) SPAM yields are generally lower than those in Ghana. Percentage increases in rice yields ranged from 10 to 76 percent. Further increasing N rates increased yields most remarkably in the Ziguinchor region of southwest Senegal (Figure 3.4).

Figure 3.4 Yield increase in Senegal due to current rate of N as UDP and doubling current rate of N as UDP



Source: Authors.

4. DISCUSSION

Many of West Africa's soils are sandy, acidic, and low in organic matter and cation-exchange capacity (Ahn 1970; Buresh 1987; Jones and Wild 1975). For that reason a smaller share of the rice growing areas in the region may be suitable for UDP compared with Bangladesh and other regions in Asia where UDP has been most successful. Based on the biophysical criteria we used in our models (primarily soil pH and texture), most of the rice growing area in Bangladesh is suitable for UDP (77 percent), yet the area of suitability makes up less than half of the current extent of rice in Ghana and Senegal and is spatially disconnected with a patchy distribution. Compared with Bangladesh, therefore, the geography of UDP suitability in Ghana and Senegal may potentially limit the scalability of UDP adoption and potential impacts at the national level. When the two African countries are compared, the extent of suitability is, however, noteworthy in Ghana (39 percent), especially in the more productive rice growing regions of Northern and Upper East, where more than 40 percent of the area is biophysically suitable for UDP. The area of suitability is much lower in Senegal (23 percent with the highest concentration in the northern region of Saint Louis) despite large yield potential under UDP adoption in several regions of the country.

While UDP has not yet been widely adopted in SSA, demonstration plots in Nigeria's Niger State have yielded 20 to 30 percent over farmers' traditional practice, and results have been stable across different locations (Liverpool-Tasie, Adjognon, and Kuku-Shittu 2014; Tarfa and Kiger 2013). In the present study, simulated increases were more modest in Ghana and ranged from 2 to 10 percent under current (low) rates of N fertilization ($\sim 20 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). Yields more than doubled, however, when we doubled (intensified) the N concentration of supergranules, although yield increases were not always intuitive based on the extent of suitability. For example, the largest yield increase in Ghana (27 percent) under the higher N scenario occurred in the Western region where more than 15,000 hectares of rice are currently grown, yet only 5 percent of the area was deemed suitable for UDP. In the more productive Northern and Upper East regions, however, where more than 40 percent of the rice area is suitable for UDP according to our analyses, yield increases remained below 10 percent under either N scenario. Although the extent of UDP suitability is lower in Senegal than in Ghana, potential yield increases with the technology are remarkably higher in Senegal since the baseline levels of rice yields are generally lower than those in Ghana. For example, yields increased astronomically under UDP simulations in the Ziguinchor region of southwest Senegal, ranging from 76 (low [N]) to 201 (high [N]) percent over farmers' traditional practices, despite the overall low extent of suitability for UDP in this region (10 percent). Such anomalies indicate large regional yield gaps in rice and opportunities for intervention, but they do not necessarily indicate the potential of substantial nitrogen savings under UDP compared with broadcasting, particularly if soils are not suitable for deep placement. If we filter results by at least 10 percent for levels of impact in terms of UDP suitability (≥ 10 percent of rice production area), area of rice production (≥ 10 percent of national share), and potential yield increase (≥ 10 percent over farmers' traditional practice), just 5 of the 21 rice growing regions throughout Ghana (Eastern and Northern) and Senegal (Kolda, Saint Louis, and Ziguinchor) fit the criteria.

Although the present study defines the suitability of UDP within particular biophysical parameters gathered from the literature—primarily soil pH and texture—it should be noted that model filters were based on a limited number of variables. In other words, maps are approximations based on best estimates of assumed-important soil parameters and may be more geographically fluid than the somewhat binary system we illustrate. In addition to suitable biophysical criteria, the successful scaling of this technology will also depend on farmers' linkages to markets and agrodealers, as well as supportive national policies and healthy extension networks that are not addressed in this study. The availability and affordability of extra labor is also particularly important and a major constraint to adoption (Mohanty et al. 1998). Recent studies reinforce the significance of extra labor requirements in SSA, especially in the absence of suitable burial tools (an ongoing development) (Liverpool-Tasie, Adjognon, and Kuku-Shittu 2014). Scaling will also rely on the establishment of a reliable supply chain of UDP briquettes and the

appropriate machinery and tools for UDP manufacturing and burial. The potential success of UDP scaling, therefore, depends on a complexity of events and requires a comprehensive value-chain approach.

In addition to SSTP, there is growing interest from national stakeholders, development partners, and donors to invest in UDP technology and bring it to scale in other regions of the world, including SSA. Beyond the theoretical impacts of UDP adoption and performance, however, this is still a novel technology in SSA. There is a clear need to fill data gaps and broaden the evidence base of UDP through, for example, on-farm farmer-organized trials, on-the-ground impact evaluations, and cost-benefit analyses. To our knowledge, there is currently only one empirical study that used in-depth surveys to analyze the characteristics of rice farmers and households who adopted UDP in the region (Liverpool-Tasie, Adjognon, and Kuku-Shittu 2014). Results from the study show that farmers who adopted UDP in two villages in Niger State, Nigeria, where UDP was actively promoted in 2011, likely managed relatively small plots and planted in pure rice culture near the homestead. Farmers who were likely to gain the most benefits from UDP already had access to hired labor and subscribed to best agronomic practices (for example, establishment of a nursery and proper timing and application of UDP). Interestingly, the study found that most farmers did not subscribe to the recommended burial depth of 7 to 10 centimeters for urea supergranules, presumably, the authors claimed, because it was too arduous, and rather practiced shallower burial depths. For those who buried urea supergranules at least 3 to 6 centimeters deep, however, yields significantly increased and did not improve with deeper depths. Overall, the authors estimated that farmers who adopted UDP in Niger State had increased rice yields by at least 15 percent.

This study demonstrates a high-level decision support strategy, especially for SSTP, by quantifying the geospatially explicit potential of UDP in lowland rice cropping systems in Ghana and Senegal. Even with limited data, we identified regions in Ghana and Senegal that are potentially suitable for UDP adoption and scaling by using a research framework that combines the characteristics of a potential technology, its grid-based geospatial extent, and potential yield increases simulated with a process-based crop model. Overall, the potential to scale UDP in Ghana and Senegal, and presumably in other West African countries, may be more limited than in Bangladesh due to the nature of the soils and presumably other socioeconomic constraints not addressed in this study (like labor and supportive national policies). Therefore, in addition to UDP a variety of interventions are currently needed to improve the production of lowland rice cropping systems and manage nutrients in Ghana and Senegal, especially where soils are not suitable for UDP.

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