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Targeting Sustainable Intensification of Maize-Based Agriculture in East Africa

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Abstract

Agricultural intensification in Sub-Saharan Africa has the chance to increase yields and food security while minimizing environmental contamination and protecting remaining native ecosystems. Targeting intensification to areas of high production potential including clayey, deep tropical soils on gently sloping lands will reduce leaching and runoff of nitrogen into water bodies. This holds particularly for rates of nitrogen fertilizer applications of less than 150 N $ha^{-1} yr^{-1}$ rates at which nitrous oxide emissions also remain low. Overlays of maps of maize production potential, soil properties, and topography for East Africa indicate almost half of that area has high production potential and a third of that is on favorable soils. More than 70% of this area identified for targeting is already in cropland, thus reducing the need to clear additional native ecosystems. Targeting intensification must also include factors such as climate and seasonality. Incorporating results from field studies of agricultural impacts, assessing these impacts at larger scales, and developing planning maps with national partners and other stakeholders are key steps toward promoting increased crop production while minimizing environmental consequences.

Keywords

sustainable, intensification, agriculture, maize, Africa

Agricultural intensification in Sub-Saharan Africa is both desirable and inevitable. Increased food production in the subcontinent has occurred primary through extensification—increasing cropland area by clearing forests, woodlands, and grasslands—from 1980 to 2000 (Gibbs, Ruesch, & Achard, 2010). More recently, deforestation in Africa from 2000 to 2005 cleared 4 million ha or the equivalent to 55% of global forest loss (Lupala, Lusambo, & Ngaga, 2014). Although the conversion of forests and woodlands may meet some of the food needs of a rapidly growing population, expanding deforestation threatens the long-term availability and equitable distribution of ecosystem services such as water for drinking and irrigation, soil fertility, pollination, fuel for energy, and forage for livestock (Power, 2010). Many ecosystem services derived from these wildlands may be attributed to their biodiversity, which declines in agriculturally dominated landscapes (Power, 2010).

Agricultural intensification, increasing crop yields and production on land that has already been converted from native ecosystems, has the potential to increase food production while simultaneously reducing deforestation and concomitant losses of biodiversity and ecosystem services (Stevenson, Villoria, Byerlee, Kelley, & Maredia, 2013). Agricultural intensification is at the heart of the African Green Revolution and is already taking place in many countries (Sanchez, 2015). Following decades of yield stagnation, low fertilizer (nutrient) inputs, and soil degradation (Sanchez, 2002), increased use of fertilizers is a key strategy to increase crop yields and reduce hunger (Denning et al., 2009; Sanchez, Denning, & Nziguheba, 2009). The Abuja Declaration (2006) set a fertilizer target for the African Green Revolution to move from 8 to 50 kg ha^{-1} of total nutrients. Cereal yields can double or triple if both improved seeds and fertilizers are used (Sanchez et al. 2007, Denning et al., 2009; Nziguheba et al. 2010, Snapp, Blackie, Gilbert, Bezner-Kerr, & Kanyama-Phiri, 2010, Sanchez, 2015). Maize yields in western Kenya increased to 6.3 t ha^{-1} with modest

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fertilizer application rates (50–75 kg N ha^{-1} yr^{-1}; Hickman, Palm, Tully, Diru, & Groffman, 2015), improved seed, and best management practices, compared to the country average yields of 1.6 t ha^{-1}. Because agricultural intensification involves higher rates of *N* fertilizer application, it also comes with potential negative environmental effects that include leaching and runoff of nitrate into ground and surface waters (Carpenter et al., 1998; Galloway et al., 2003) and higher emissions of nitrous oxide (N_2O), a powerful greenhouse gas.

Soil type, which varies widely across Sub-Saharan Africa (Dixon, Gibbon, & Gulliver, 2001; Dewitte et al., 2013), plays a key role in controlling these environmental consequences of fertilizer application. In a field trial in Western Kenya with rates of N fertilizer application of 0 to 200 kg N ha^{-1} yr^{-1}, recovery in maize was high (70%) and most of the excess N applied in the 200 kg N treatment was held in the deep, clayey soil profile and not lost to leaching below 4 m (Tully, Hickman, McKenna, Neill, & Palm, 2016). This low leaching is likely attributable to anion exchange sites on the weathered clay that hold nitrate in the soil profile and protect it from leaching (Mekonnen, Buresh, & Jama, 1997; Shepherd, Buresh, & Gregory, 2000). In contrast, maize grown on a sandy soil in central Tanzania fertilized with the same N rates fertilizer application rates as the trial in Western Kenya had low yields of 1.1 t ha^{-1} and fertilizer use efficiency. Although nitrate leaching below 50 was low because of low rainfall, N was retained in surface soils as ammonium (Tully et al., 2016), and this N could be nitrified and susceptible to leaching with the next rains and little clay to retain N in the soil profile. We suspect that anion exchange, likely widespread in the clayey soils in tropical regions, will play a key role in controlling watershed-scale N losses under higher N fertilization rates. However, though, there is much we do yet know about the presence and role of this deep profile nitrate storage or the long-term ability of soils to continue to retain nitrate after years of higher fertilizer additions.

Recent work also shows that fluxes of N_2O in Kenya are also low despite N fertilizer application rates up to about 150 kg N ha^{-1} (Hickman et al., 2015; Hickman, Palm, Melillo, Mutuo, & Tang, 2014). These patterns of low rates of N leaching and N_2O emissions from East Africa are supported by similar findings in the intensive, N-fertilized maize rotations on highly weathered, clayey soils in the seasonally dry lowland region of the Amazon (O'Connell, 2015; Neill et al., this volume). Combined, these new results suggest that intensification of maize cropping could produce high yields while maintaining relatively low environmental impacts of N_2O emissions and N leaching if fertilizer use is targeted on clayey, weathered soils that have relatively flat topography with relatively little surface runoff, and if fertilizer use remains below a threshold of about 100 to 150 kg N ha^{1}. These threshold rates are far above the target of the Abuja Declaration and not likely to be exceeded in the near future.

We used a series of maps of East Africa to explore areas for targeting agricultural intensification that have the potential to minimizing losses of N to the environment and to protect remaining wildlands by allowing greater production on existing cropland.

Methods and Results

We explored the overlays of maps of maize suitability from International Institute for Systems Analysis (IIASA) (Pugh et al., 2016), soil properties from International Soil Reference and Information Centre/Africa Soil Information Service (ISRIC/AfSIS) (Hengl et al., 2014), digital elevation models, and agricultural landcover maps (Thenkabail et al., 2012) and forest cover maps (Hansen et al., 2013) to locate areas that are suitable and available to target for agricultural intensification. We included Burundi, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda. We defined the criteria as follows: (a) maize suitability areas classified by IIASA as 1, 2, or 3 would be the best areas for increasing yields and areas classified as 4 or greater were assumed to be marginal for increasing yields substantially; (b) soils with clay content above 30% represented the weathered and deep soils where yields could increase with low leaching and low N_2O emissions in response to N fertilization; and (c) soils with slopes less than 8% where surface runoff will be limited. The Geographic Information System (GIS) layers representing these parameters were simplified to binary yes/no layers based on these parameters, and these three binary layers were then combined to create a binary convergence layer where all three conditions were met. The convergence layer was then applied to the agricultural landcover and forest

Table 1. Percentage of Total Area and Area in Different Categories of Criteria for Targeting Agricultural Intensification in the Six East African Countries.

Category of criteria for targeting intensification	Percentage of total land area	Area in different categories (sq km)
Top 3 maize suitability model classes	43.9	1,091,454
Clay > 30%	57.7	1,435,634
Slope <8%	70.53	1,753,770
	70.5	1,753,770
Clay >30 and Slope <8%	33.7	837,908
Slope <8 and Maize 1, 2, 3	29.9	742,514
Clay <30 and Maize 1, 2, 3	26.2	651,238
Convergence areas of clay, slope, and maize suitability	15.1	376,031

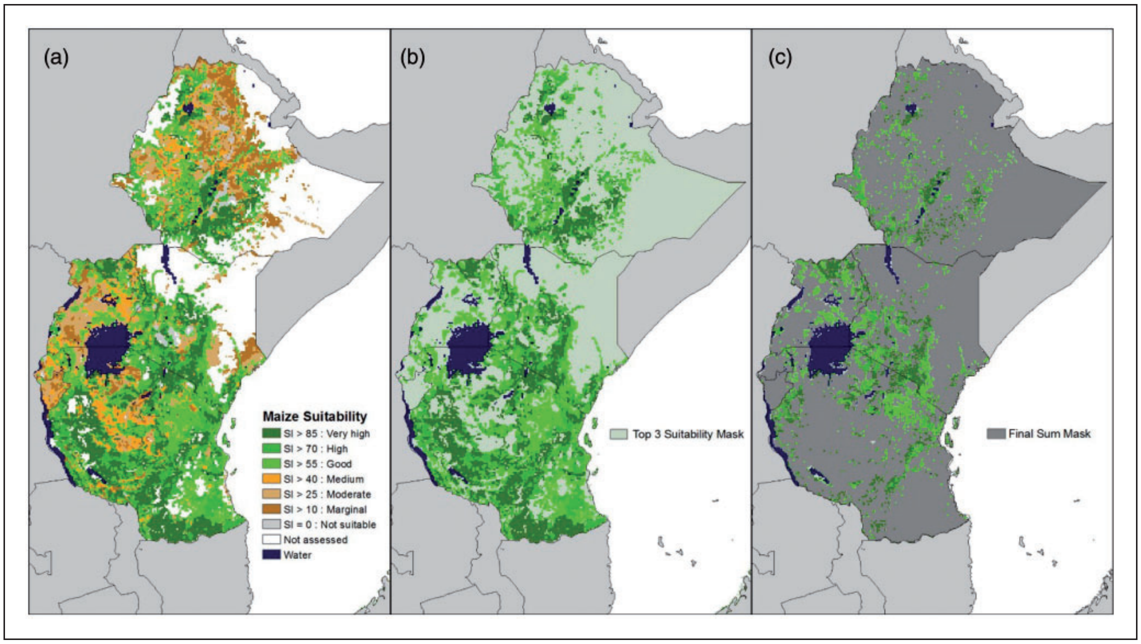

Figure 1. Resulting maps for targeting maize intensification in East African countries showing the resulting location of (a) all maize suitability categories, (b) maize suitability Categories 1, 2, and 3, and (c) the location of overlay of areas of maize suitability Categories 1, 2, and 3 with areas having soils with percentage clay content >8% and slope of land <8%.

cover maps to evaluate what areas were either already classified as cropland or areas with less than 10% tree cover to avoid cropping in remaining relatively intact forests and woodlands.

Results from the analysis showed an area of 1,091,454 km^2 was contained in maize suitability Classes 1, 2, and 3 or 44% of the total area of the region (Table 1). The percentage of land in the maize suitability Classes 1, 2, and 3 varied considerably from almost 70% in Tanzania to only 6% in Burundi. A third of the total area was on relatively flat land and with high clay contents that would likely result in less nutrient losses to water bodies and the atmosphere (Table 1). Only about 15% of the total area, however, contained an overlap of the top three maize suitability classes with the soil properties of clay >30% and slope <8% (Table 1; Figure 1). In addition, about 70% of that area considered suitable for targeting is already in cropland. Many of these croplands currently have low yields that could, through intensification, increase by 3 to 5 t ha^{-1} and take the pressure from existing wildlands.

Discussion

Meeting both goals of increasing food production and reducing environmental impacts requires policies that simultaneously support agricultural production and protect wildlands—neither goal alone will happen without supporting policies. Tools that provide policy makers with spatially explicit information on where and how to focus agricultural intensification activities could be an important tool for promoting sustainable agricultural intensification. We have provided one such example, the criteria can be adjusted or new criteria included to refine targeting and to address different crops and farming systems. Interpreting the results from direct field studies of agricultural impacts, assessing these impacts at larger scales, and developing planning maps with national partners and other stakeholders are key steps toward promoting expanded maize production while minimizing environmental consequences of more intensive maize production. For agricultural intensification to take off in Sub-Saharan Africa, in addition to targeting intensification to increase productivity while minimizing environmental benefits, governments must address the multiple barriers faced by smallholder farmers in the region to intensify agricultural production including climate and financial risks, lack of credit facilities and markets, and challenging infrastructure.

Declaration of Conflicting Interests

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References

Abuja Declaration. (2006). Retrieved from https://www.afdb.org/en/topics-and-sectors/initiatives-partnerships/african-fertilizer-financing-mechanism/abuja-declaration/

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarthm, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, *8*, 559–568.

Galloway, J. N., Aber, J. D., Erisma, J. W., Sietzinger, S. P., Howarth, R. W., Cowling, E. B., & Cosby, B. J. (2003). The nitrogen cascade. *BioScience, 53*, 341–356.

Dixon, J. A., Gibbon, D. P., & Gulliver, A. (2001). *Farming systems and poverty*. Rome, Italy: Food and Agriculture Organization.

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., . . . Sachs, J. (2009). Input subsidies to improve smallholder maize productivity in Malawi: Toward an African green revolution. *PLoS Biology*, *7*, e23.

Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., . . . Zougmore, R. (2013). Harmonisation of the soil map of Africa at the continental scale. *Geoderma*, *211–212*, 138–153.

Gibbs, H. K., Ruesch, A. S., & Achard, F. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences*, *107*, 16732–16737.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., . . . Townshend, J. R. G. (2013). *High-resolution global maps of 21st-century forest cover change*. *Science*, *342*, 850–853.

Hengl, T., de Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B. M., Ribeiro, E., . . . Gonzalez, M. R. (2014). SoilGrids1km—Global soil information based on automated mapping. *PLoS One*, *9*(8): e105992. doi:10.1371/journal.pone.0105992.

Hickman, J. E., Palm, C. A., Melillo, J. M., Mutuo, P., & Tang, J. (2014). Nitrous oxide responses to increasing fertilizer inputs in well-managed smallholder agriculture in Kenya. *Nutrient Cycling in Agroecosystems*, *100*, 177–187.

Hickman, J. E., Palm, C. A., Tully, K. L., Diru, W., & Groffman, P. M. (2015). A nitrogen tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes with intensification. *Journal of Geophysical Research: Biogeosciences*, *120*(5): 938–951.

Lupala, Z. J., Lusambo, L. P., & Ngaga, Y. M. (2014). Management, growth, and carbon storage in Miombo woodlands of Tanzania. *International Journal of Forestry Research*. Retrieved from http://dx.doi.org/10.1155/2014/629317Z

Mekonnen, K., Buresh, R. J., & Jama, B. (1997). Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields. *Plant Soil*, *188*, 319–327.

Neill, C., Jankowski, K., Brando, P. M., Coe, M. T., Deegan, L. A., Macedo, M. N., & Krusche, A. V. Surprisingly modest water quality impacts from expansion and intensification of large-scale commercial agriculture in the Brazilian Amazon-Cerrado region. *Tropical Conservation Science*.

Nziguheba, G., Palm, C. A., Berhe, T., Denning, G., Dicko, A., Diouf, O., . . . Sanchez, P. A. (2010). The African green revolution: Results from the millennium villages project. *Advances in Agronomy*, *109*, 75–115.

O'Connell, C. S. (2015). *Ecological tradeoffs to an agricultural Amazonia: Investigating the effects of increased agricultural production on Amazonia's contribution to global climate and nitrogen cycling* (PhD dissertation, p. 200). St. Paul: University of Minnesota.

Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transaction of the Royal Society B*, *365*, 2959–2971.

Pugh, T. A. M., Muller, C., Elliot, J., Derynbg, D., Folberth, C., Olin, S., . . . Arneth, A. (2016). Climate analogues suggest limited potential for intensification of production on current croplands under climate change. *Nature Communications*, *7*, 12608. doi:10.1038/ncomms12608.

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, *295*, 2019–2020.

Sanchez, P. A. (2015). En route to plentiful food production in Africa. *Nature Plants*, *1*, 1–2.

Sanchez, P. A., Denning, G. L., & Nziguheba, G. (2009). The African Green Revolution moves forward. *Food Security*, *1*, 37–44.

Sanchez, P., Palm, C., Sachs, J., Denning, G., Flor, R., Harawa, R., . . . Zamba, C. (2007). The African millennium villages. *Proceedings of the National Academy of Sciences*, *104*, 16775–16780.

Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., & Kanyama-Phiri, G. Y. (2010). Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences*, *107*, 20840–20845.

Shepherd, G., Buresh, R. J., & Gregory, P. J. (2000). Land use affects the distribution of soil inorganic nitrogen in smallholder production systems in Kenya. *Biology and Fertility of Soils*, *31*, 348–355.

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T., & Maredia, M. (2013). Green revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proceedings of the National Academy of Sciences*, *110*, 8363–8368.

Thenkabail, P. S., Knox, J. W., Ozdogan, M., Gumma, M. K., Congalton, R. G., Wu, Z., . . . Nagler, P. (2012). Assessing future risks to agricultural productivity, water resources and food security: how can remote sensing help? Photogrammetric Engineering and Remote Sensing. *Special Issue on Global Croplands: Highlight Article*, *78*(8): 773–782.

Tully, K. L., Hickman, J., McKenna, M., Neill, C., & Palm, C. A. (2016). Effects of increased fertilizer application on inorganic soil N in East African maize systems. *Ecological Applications*, *26*, 1907–1919.