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Executive Summary

In Africa, achieving sustainable agricultural intensification – increasing agricultural output without deleterious environmental impacts or converting more land for cultivation – will depend greatly on the actions of smallholder farmers and the policies that influence them. Whatever the future holds, the vast majority of farmers right now are small scale. Using multiple lines of evidence across disciplines, we examine trends in productivity of land and fertilizers in Malawi.

Malawi has been a trend-setter for agricultural policies in Africa for decades. The country's focus on maximizing staple production through input subsidies, mainly for fertilizer, has been adopted by numerous other African governments. In fact, one out of every 14 people on Earth live in an African country that subsidizes fertilizer as its primary strategy for promoting sustainable agricultural intensification.

Unfortunately, this study uncovers disturbing trends that indicate intensification and sustainability are at risk in Malawi. Two time-series datasets of satellite-based vegetative indices show a generally flat but highly variable productivity trend on agricultural land, with certain periods and locales of steep decline. This is notably despite substantial (and successful) government effort to promote fertilizer use.

We also compile field-level evidence from several studies over three decades that are consistent with significant declines in maize yield response to fertilizer over time. These trends could be related to soil degradation, as the disappearance of fallow land and minimal investment in rehabilitation practices in densely populated areas put agricultural productivity in jeopardy.

These signs of the harmful impacts that narrowly focused policies may be having in Malawi are a warning to policy makers in the country and around the continent that a more holistic strategy that considers soil health will be necessary for sustainable intensification in agriculture.

Helping smallholder farmers achieve greater yield response to fertilizers, and thus greater yields, will require management practices that promote resilient crop productivity and healthy soils over the long term. Such practices include organic amendments used in combination with more tailored fertilizer blends containing micro-nutrients. Innovations in extension and agricultural policy will be required to enhance farmers' management practices and adoption of sustainable intensification. This includes using information communication technology, participatory extension that builds on indigenous knowledge, and expanding informal and formal market systems for access to seeds and other inputs.

Bi-directional learning will also be important: solutions must be worked out on farmers' fields. This is clear from the gap between maize response to nitrogen on farmer-managed vs. researcher-managed fields. Real solutions will be localized and heterogeneous across farms, even within a given village and according to households' resources, soil quality, position in maize markets, and ability. In sum, increasing fertilizer use may be necessary but is not sufficient to achieve sustainable intensification.

Widespread use of integrated soil fertility management (ISFM) and attention to soil health are also needed. Malawi and other African governments could reflect this understanding in their policies and programs to achieve sustainable intensification. The Africa Union-led Abuja II process explicitly identifies soil health, resilience and ISFM as important components of a comprehensive strategy to raise fertilizer use and achieve sustainable agricultural intensification in Africa. The sooner policies and policy makers embrace this acknowledgement, the sooner these troubling trends can be reversed or avoided.

1. Introduction

Sustainable agricultural intensification means increasing agricultural output over time without adverse environmental impacts and without the conversion of more land for cultivation (Baulcombe et al., 2009). This is no small task. In Africa, smallholder farmers have an important role in achieving this goal; they account for about 70% of the continent's domestically produced calories and roughly half of its cultivated land (Samberg et al., 2016).

Through collaborative engagement across the disciplines of agro-ecology, soil science, geography and agricultural economics, we aim to uncover sustainability trends in the Malawi smallholder sector. Malawi provides an important and unique lens through which to view progress in meeting sustainable development goals. It is unique in that it is a relatively small and densely populated country, but it is important because these characteristics make the country a bellwether on the continent with a rapidly growing population. Malawi is also a leading example in the policy sphere. The country's efforts to increase farmer access to agricultural inputs through sustained government commitment has provided an example followed my numerous other countries (Denning et al., 2009; Jayne et al., 2018). Transdisciplinary research provides the means to assess trends in agricultural sustainability utilizing a range of indicators developed by various research disciplines (Lang et al., 2012), and here reveals concerning evidence that intensification and sustainability are in jeopardy in this country.

Understanding soil health status is integral to assessing whether sustainable intensification is underway. Yet long-term trends in soil degradation remain largely unknown in Africa (Tully et al., 2015). Using measures of plant "green-ness", which generally reflects crop productivity, it is possible to assess whether plants are taking up more nitrogen (Zhu et al., 2012; Burke and Lobell, 2017; Messina et al., 2017). Recent evidence from Ghana and Malawi, based on satellite imagery and household surveys, shows that although subsidies are enhancing farmer access to fertilizers, this is not necessarily leading to the expected gains in crop productivity (Jayne et al., 2018; Burke et al., 2020; Scheiterle et al., 2019). If fertilizers are being used ineffectively, a trajectory of unsustainability could be self-reinforcing in that low crop response rates to nitrogen lead to poor plant growth and few residues, which in turn could compromise soil structure and nutrient retention and lead to even lower response rates (Ranaivoson et al., 2017). Household surveys reveal wide variation in farmer-reported rates of maize yield response to fertilizer, from nil to 21 kg grain/kg N-fertilizer across East and Southern Africa (Jayne et al., 2018; Roobroeck et al., 2020). Fertilizer use becomes unprofitable – and thus unsustainable – if response rates are low.

Understanding levels and trends in crop yields and yield response to fertilizers on smallholder fields is thus integral to assessing whether sustainable intensification is in fact occurring.

2. Background

Our analysis investigates several lines of evidence through a multi-disciplinary lens based on rural surveys and remote sensing to assess crop productivity trends on cultivated lands in Malawi. This land-locked country in Southeastern Africa has been referred to as the heart of the African green revolution, catalyzed through substantial investments in fertilizer subsidies (Sanchez, 2002; Denning et al., 2009). Seventy percent of Malawian employment is in agriculture and the vast majority of farmers (76%) are operating on less than one hectare (Muyanga et al., 2020).

Malawi's densely populated rural areas face intensification challenges similar to many other densely populated areas of rural Africa (Jayne et al., 2019). Rising population densities are making reliance on area expansion infeasible for millions of African farmers (Schneider et al. 2011). The arable land frontier in Malawi has already been reached in many smallholder areas, causing farms to become subdivided, fragmented, and increasingly small. Smallholders have responded to shrinking farm sizes by more continuously cropping their fields, mainly with their priority staple, maize (Thierfelder et al., 2013). Fallows have largely disappeared in densely populated areas of Malawi. In sub-Saharan Africa overall, fallowed land as a proportion of total farmland has declined steadily from 40% in 1960 to 15% in 2011 (Fuglie and Rada, 2013). Adoption of integrated soil fertility management (ISFM) practices has remained stubbornly low in Malawi, as in many other parts of the region (Katengeza et al., 2019; Kopper et al., 2020; Place et al., 2003). ISFM includes replacing nutrients (possibly with inorganic fertilizers), but also addresses the impact agriculture can have on the biological and chemical properties of soil (e.g., by incorporating residues to maintain soil carbon levels, or, if needed, applying lime to manage soil acidity) (Jones et al., 2013).

Longitudinal data over three decades provides a unique opportunity to explore Malawi rural household survey data and remotely sensed time-series of crop productivity. Examining these multiple lines of evidence together brings some warning signs into focus and highlights the value of transdisciplinary approaches.

3. Results

3.1 Malawian Productivity Trends

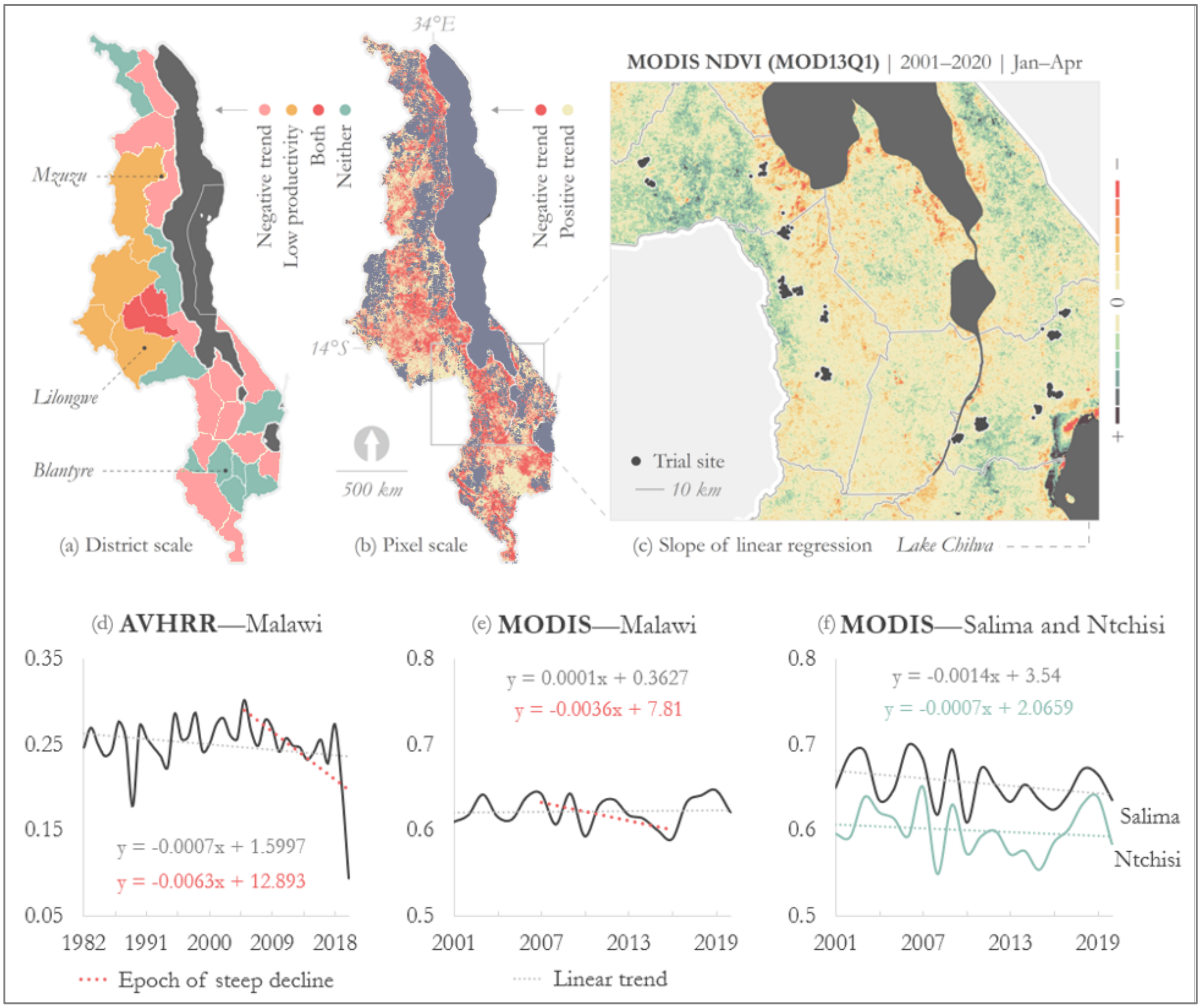
Crop productivity across Malawi from 2001–2020 was measured using the average January–April normalized difference vegetation index from NASA's Moderate Resolution Imaging Spectoradiometer (MODIS NDVI; see methods annex and Didan et al., 2015). Results highlight the spatial organization of agricultural productivity trends across Malawi (Figure 1). Large swaths of the terrain show marginal to moderate decreasing productivity and there are notable decreasing slopes in the Lilongwe District area (a densely cultivated region) and the area to the southern/southwestern edge of Lake Malawi.

Across the temporal range of available data for MODIS NDVI (2001–2020), there is a very slight positive linear trend in greenness at the national level; however, there is an epoch of steep decline from 2007 to 2016 (denoted with a dotted red line in Figure 1, panel e). By comparison, data from USGS Advanced Very High-Resolution Radiometer (AVHRR) exhibits a subtle negative linear trend over a longer period from 1982 to 2020. These data also show an epoch of steep decline between 2005 and 2020, roughly corresponding to the epoch identified using MODIS NDVI data. Notably, the district of Salima exhibited the steepest overall decline, and Ntchisi and Dowa both exhibit negative slopes and comparatively low productivity.

For MODIS NDVI, 54% of agricultural land exhibited a positive linear trend between 2001 and 2020 and 46% exhibited a negative linear trend (Figure 1, panel b). Both MODIS and AVHRR show an uptick in 2018, followed by a downtick in 2020, which is most pronounced in the AVHRR data. Distinct periods of low productivity emerge in the MODIS NDVI data in 2001, 2005, 2008, 2010, and 2016. Considering the oscillation of productivity trends between 2001 and 2016 (the year showing the lowest productivity in MODIS NDVI), it is reasonable to infer that production in Malawi may trend downwards in the near future.

Furthermore, averaging over space to the national level masks substantial variation at other spatial scales. For example, we can focus on Central Malawi, where experimentation on hundreds of on-farm sites has been carried out since 2013 in conjunction with annual household surveys that monitor over 1,200 plots (Burke et al., 2020; Snapp et al., 2018; Wang et al., 2019). Malawi contains many agroecological zones across its latitudinal extent, and the types of crops grown and surrounding vegetation varies by region. At the extension planning area (EPA) scale, the Golomoti sites in particular (where maize is a staple) exhibit

Figure 1. Remote Sensing Evidence of Malawian Productivity Trends



Panel notes: (a) District scale agricultural productivity trends on agricultural land, with low productivity defined as one standard deviation below the country mean; (b) pixel-scale vegetation productivity trends (gray areas indicating non-agricultural land); (c) slope of the linear regression line for vegetation productivity (not masked to agricultural land) with trial site locations overlain. Time-series charts were produced by aggregating agricultural productivity at the country and district scales. The datasets analyzed during the current study and code for extracting data are available in the Harvard Dataverse repository (Peter et al., 2021, also see: https://doi.org/10.7910/DVN/M4ZGXP)

a marked decreasing productivity trend between 2001 and 2020. Of the trial sites at Golomoti (N = 115), 96% exhibit a decreasing linear trend (as measured via MODIS NDVI).

Weather may explain some deviations from mean or trends in Malawi's NDVI in a given year, as variable rainfall has long been the pattern in Malawi (Nicholson, 2017). However, an overall decline in precipitation in Malawi is not clearly discernable during these periods, so total precipitation is not likely responsible for downward NDVI trends. Extreme weather events could be contributing. The last two decades in Malawi has seen localized changes in the numbers of extreme weather events that include both more and less frequent incidences of dry spells and floods in different areas (Haghtalab et al., 2019). Higher overall temperatures, including at night, could be leading to drier growing conditions and decreasing NDVI (Mulenga et al., 2016).

Conversely, declining access to fertilizer cannot explain the downward trajectory in NDVI. Between 2009 and 2014, a period of steep productivity decline, fertilizer N applications in Malawi increased from 72,000 tonnes of N to over 118,000 tonnes of N nationally (FAOSTAT, 2020). This is largely attributable to growth in the Farm Input Subsidy Program (FISP), which, by 2014, was distributing nearly 210,000 tonnes of fertilizer (Jayne et al., 2018). The majority of farm families had access to fertilizer throughout the FISP period (Lunduka et al., 2013). Household surveys conducted in Golomoti and nearby sites in Central Malawi report usage of 76 to 98 kg fertilizer N per ha on maize plots over 2015–2018 (Burke et al., 2020).

Beyond the rise in fertilizer use, there is no evidence to suggest widespread changes in agronomic management in Malawi. The use of hybrid maize has remained generally consistent, at about 60%, and only slight improvements in crop population densities and weed control measures have been reported in recent years (Lunduka et al., 2013; Wang et al., 2019).

Barring other explanations, the logical inference is that poor or declining soil fertility is driving the declining and variable NDVI values seen on cultivated lands. Soil organic matter and phosphorus status are low to very low on the vast majority of smallholder fields, as reported in FAO data and in a country-wide survey of 2,000 smallholder farms conducted in the early 1990s (Snapp, 1998). Degraded soil properties were also reported in a 2014 pedology survey that revisited many 1990 FAO sites, with the highest depression in soil organic carbon being associated with intensively cultivated fields (Mpeketula, 2016).

Considering the sum of evidence from these two remote sensing NDVI sources over multiple decades, the productivity trends - high variability and periods of steep decline - are counter to expectations based on widespread use of fertilizer. Aggregate-level data may mask important factors at plot level or interactions between productivity determinants like rainfall and fertilizer that could explain the variation in trends show in Figure 1 (panel b). These conclusions, however, are consistent with trends in recent field-based evaluations of crop response to fertilizer in Malawi.

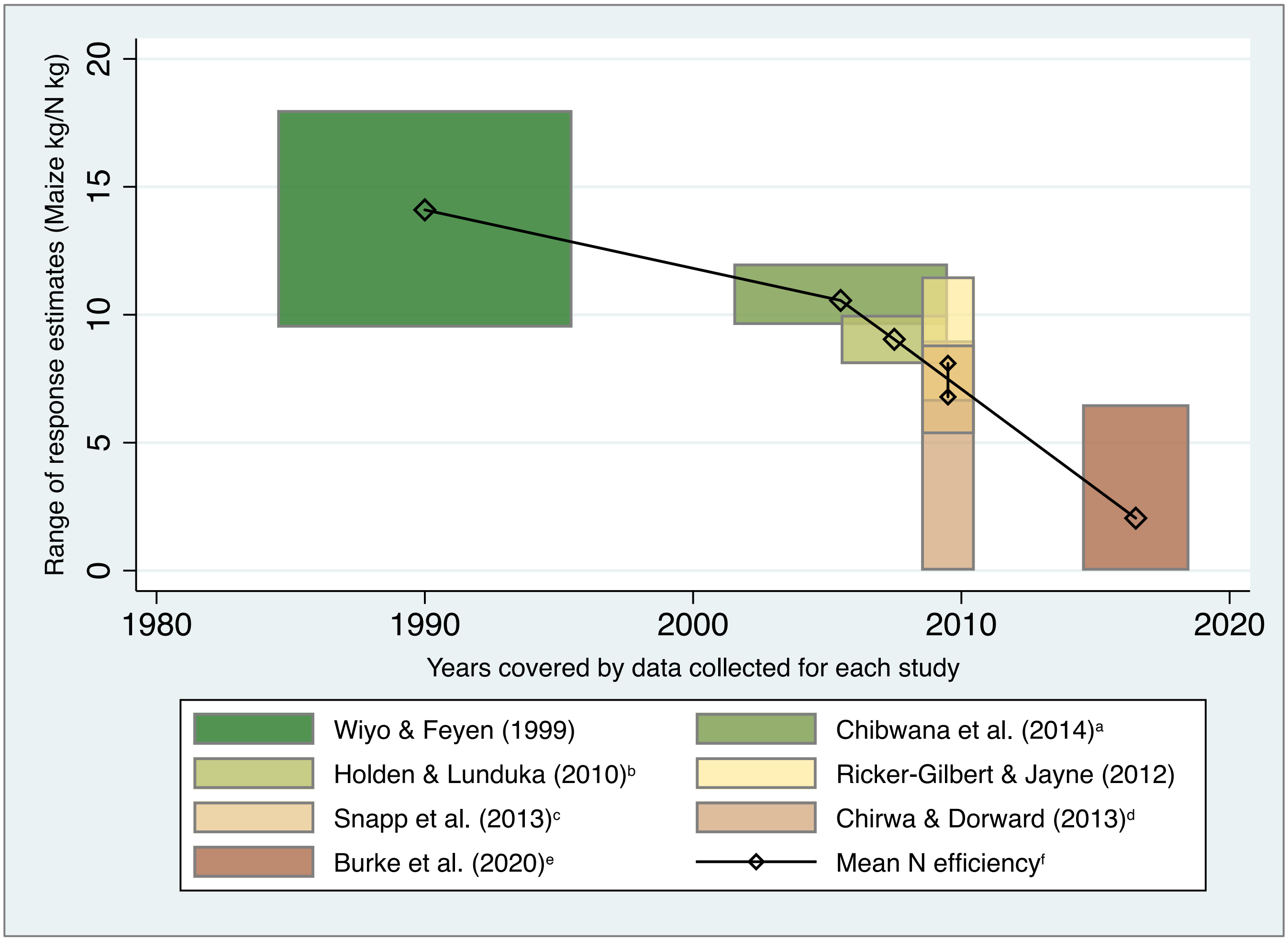
3.2 Declining Maize Yield Response to Nitrogen

The decline in productivity over a time period of increasing fertilizer use demonstrates that increased fertilizer use alone is not sufficient to achieve sustainable agricultural intensification, and that fertilizers are contributing less to agricultural output than commonly believed. We examine this by reviewing studies published in the past several decades that examined yield response to fertilizer on farmer-managed maize fields. We exclude studies of fertilizer effectiveness conducted on researcher-managed fields or in trial plots. The latter can be used to understand the potential yield response, or the upper bound of what a farmer might achieve, but there are many reasons not to expect those yield responses on farms (Snapp et al., 2014). Instead, we focus on studies that have estimated yield responses based on farmer surveys.

To the best of our knowledge, there have been seven major studies on yield response to fertilizer carried out using Malawian farmer data since 1984. These are summarized in Figure 2, where each study is represented by a box that describes the years data were collected on the horizontal axis, the range of yield responses to nitrogen estimates on the vertical axis, and a point corresponding to the mean year and yield response. We note that not all of these studies are nationally representative, but taken together, they provide a longitudinal view of maize yield response to nitrogen fertilizer in Malawi.

The earliest study from Wiyo and Feyen (1999) used data from the nationally representative Annual Sample Survey of Agriculture collected by the Ministry of Agriculture between 1984 and 1995. They estimated yield responses between 9.5 maize grain kg per kg of N applied (kg/kg) and 16.5 kg/kg for local maize varieties and 14-16 kg/kg for hybrids. They estimated a national mean response of 14.1 kg/kg. For context, in the same year, the Maize Productivity Task Force reported potential yield responses between 19 and 26 kg/kg on trial plots in Malawi (MPTF, 1999). Chibwana et al. (2012), using data from Malawi's Central and Southern Regions collected between 2002 and 2006, estimate a range from 9.6-12 kg/kg. Using a different random sample of Central and Southern Region farmers, Holden and Lunduka (2010) estimated that between 2006 and 2009 the mean yield response was 9.0 kg/kg. Using nationally representative data from Malawi's Integrated Household Surveys that cover 2008 to 2010, three different studies estimate response rates ranging from effectively nil to 11.5 kg/kg (Chirwa and Dorward, 2013; Snapp et al., 2013; Ricker-Gilbert and Jayne, 2017). Snapp et al. (2014) disaggregated their estimates between monocropped maize (5.3 kg/kg) and intercropped maize (8.8 kg/kg). Most recently, Burke et al. (2020) use data from the Central Region collected from 2014 to 2018 to estimate plot-specific yield responses ranging from nil to 6.5 kg/kg with a mean of 2.1 kg/kg, depending on soil and field

Figure 2. Yield response to N on farmer-managed fields over time (1984-2018) in Malawi



Sources correspond to the color coding in the legend. The box representing each study spans the range of each's yield response estimates on the vertical axis, and the years covered by their data along the vertical axis. For example, Wiyo and Feyen estimated response rates from 9.5 to 16.5 using data collected between 1984 and 1995.

a – Yield response not computed by original authors; range estimates come from Arndt et al. (2016). Overall mean calculation assumes 60% hybrid and 40% local varieties.

b – Yield response not computed by original authors; estimated range is based on the 95% confidence interval of the yield response to "fertilizer" as Holden and Lunduka (2010) report in Table 13 (page 25). To convert this to N efficiency we assume "fertilizer" is equal parts urea (46% N) and blended (23% N).

c – Range reflects different estimates for intercropped and monocropped maize; for weighted mean calculation we assume 41.7% intercropping as was reported for the relevant years by Snapp et al. (2014).

d – The authors' original estimated range includes negative values (not shown), no sample mean reported.

e – Range reflects 16 management and soil regimes. Original estimated range includes negative values (not shown).

f – Means are plotted at the mid-point for the period covered by each sample. All means are weighted and either as reported by the original authors or described in notes a-e. The line intersects the year 2010 at the average across the multiple studies for that year.

management conditions. This most recent study produces the lowest estimates to date. Notably, this study also uses the most rigorous methods of measuring yield (based on yield cuts standardized for moisture content) and soil characteristics (allowing for multiple soil regimes determined by laboratory assessed soil tests). However, given the drastically low measurements, it will be important to see these results corroborated.

The salient point emerging from these studies is a distinctly downward trend over time in Malawian maize yield response to fertilizers. These findings are consistent with the remote sensing data shown earlier and mounting evidence of low responsiveness of cereal and legume yields to nitrogen fertilizer application across many smallholder settings in sub-Saharan Africa (Roorbroeck et al., 2020).

4. Conclusions and Implications

This transdisciplinary compilation of evidence shows the value of multiple perspectives to uncovering temporal and spatial trends in productivity and resource efficiency. This collaboration has identified troubling signs regarding the sustainability of intensification trends on maize fields in Malawi – with implications for numerous African countries. For agricultural production to be either more intensive or sustainable, corrective action is needed.

Multiple lines of evidence highlighted that intensification through subsidies of inorganic fertilizer has not been sufficient. Sustainable forms of fertilizer-based intensification require sufficiently high and consistent crop response to fertilizer. The long-term trend of declining yield response to fertilizer has been overlooked as an important sustainability indicator. For now, the decline of fertilizer's effectiveness may be a more immediate problem in Malawi than other countries. Due to the country's high and growing population densities, the frontiers of unused arable land may have already been reached in many areas, leading to smaller farms and less fallowing. Other things being equal, this can lead to a decline in the soil characteristics that facilitate plant uptake of fertilizer nutrients. Unless yield response to fertilizers can be raised substantially, the effective demand for fertilizers will remain depressed below use rates needed to maintain sustainable intensification.

While the problem may be more immediate in Malawi, the warning signs are relevant for many countries on the continent. Following Malawi's lead, several governments have pursued policies that are aimed at maximizing staple production by subsidizing inputs (usually fertilizer) (Jayne et al., 2018). These include Burkina Faso, Ethiopia, Ghana, Kenya, Mali, Nigeria, Senegal, Tanzania, and Zambia. These 9 countries plus Malawi account for 42% of Africa's population (FAOSTAT, 2020). In fact, one out of every 14 people on Earth live in an African country that subsidizes fertilizer as its primary strategy for promoting sustainable agricultural intensification. For all of these countries, land is ultimately a finite resource. While arable land frontiers may be farther away in other places than they are in Malawi, Malawi is the bellwether. The multiple lines of evidence compiled here suggest that, as a myopic strategy, Malawi's example can lead to soil degradation, declining yields and low yield response to fertilizer in the long run. A narrow focus on applying nutrients as chemical fertilizer is not agronomically sustainable.

Helping smallholder farmers achieve greater yield response to fertilizers, and thus greater yields, will require management practices that promote resilient crop productivity and healthy soils over the long term. Such practices include organic amendments used in combination with fertilizers (Place et al., 2003) and more tailored use of fertilizer blends containing micro-nutrients whose low levels otherwise constrain yield response to N (Sanchez, 2019; Roorbroeck et al., 2020). Innovations in extension and agricultural policy will be required to enhance farmers' management practices and adoption of sustainable intensification. This includes information communication technology, participatory extension that builds on indigenous knowledge, and expanding informal and formal market systems for access to seeds and inputs along with education (Barakabitze et al., 2017). Bi-directional learning will also be important: solutions must be worked out on farmers' fields (Jayne et al., 2019; Kerr et al., 2019). This is clear from the gap between maize response to N on farmer-managed vs. researcher-managed fields. Real solutions will be localized and heterogeneous across farms, even within a given village and according to households' resources, soil quality, position in maize markets, and ability.

In sum, raising fertilizer use may be necessary, but it is not sufficient to achieve sustainable intensification. Widespread use of ISFM and attention to soil health are also needed (Pretty et al., 2018; Snapp et al., 2018). African governments could reflect this understanding in their policies and programs to achieve sustainable intensification. Ethiopia, for example, employs roughly half of all of sub-Saharan Africa's extension agents and, not coincidentally, has seen more agricultural growth than any other African country in the past two decades (Jayne and Sanchez, 2021). The Africa Union-led Abuja II process explicitly identifies soil health, resilience and ISFM as important components of a comprehensive strategy to raise fertilizer use and achieve sustainable agricultural intensification in Africa (AFAP, 2020). The sooner and more emphatically policies and policy makers begin to reflect this acknowledgement, the sooner these troubling trends can be reversed or avoided.

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References

AFAP (African Fertilizer and Agribusiness Partnership), 2020. *Africa Fertilizer Map 2020*. https://www.afap-partnership.org/africa-fertilizer-map-2020/

Arndt, C., Pauw, K. and Thurlow, J., 2016. The economy-wide impacts and risks of Malawi's farm input subsidy program. *The American Journal of Agricultural Economics, 98(3)*, pp.962-980.

Barakabitze, A.A., Fue, K.G. and Sanga, C.A., 2017. The use of participatory approaches in developing ICT - based systems for disseminating agricultural knowledge and information for farmers in developing countries: The case of Tanzania. *The Electronic Journal of Information Systems in Developing Countries, 78(1)*, pp.1-23.

Baulcombe, D., Crute, I., Davies, B., Dunwell, J., Gale, M., Jones, J., Pretty, J., Sutherland, W. and Toulmin, C., 2009. *Reaping the benefits: science and the sustainable intensification of global agriculture.* The Royal Society.

Burke, M. and Lobell, D.B., 2017. Satellite-based assessment of yield variation and its determinants in smallholder African systems. *Proceedings of the National Academy of Sciences, 114(9)*, pp.2189-2194.

Burke, W.J., Snapp, S.S. and Jayne, T.S., 2020. An in-depth examination of maize fertilizer response in Central Malawi reveals low profits and too many weeds. *Agricultural Economics 51(6)*, pp. 923-940.

Chibwana, C., Fisher, M. and Shively, G., 2012. Cropland allocation effects of agricultural input subsidies in Malawi. *World Development. 40 (1)*, pp. 124-133.

Chirwa, E., and Dorward, A., 2013. *Agricultural Input Subsidies: The Recent Malawi Experience*. Oxford, UK: Oxford University Press.

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., ... and Keating, M., 2009. Input subsidies to improve smallholder maize productivity in Malawi: Toward an African green revolution. *PLOS Biology, 7(1)*, e1000023.

Didan, K., 2015. MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-05-05 from https://doi.org/10.5067/MODIS/MOD13Q1.006

FAOSTAT, 2020. Annual time series data for agricultural use of nitrogen (N) fertilizer for Malawi. Available at: http://www.fao.org/faostat/en/#data/RFN, last accessed January 2021.

Fuglie, K. and Rada, N., 2013. "Resources, policies, and agricultural productivity in sub-Saharan Africa". USDA-ERS Economic Research Report, (145). Washington, D.C.

Haghtalab, N., Moore, N. and Ngongondo, C., 2019. Spatio-temporal analysis of rainfall variability and seasonality in Malawi. *Regional Environmental Change, 19(7)*, pp.2041-2054.

Holden, S. and Lunduka, R., 2010. "Too poor to be efficient? Impacts of the targeted fertilizer subsidy programme in Malawi on farm plot level input use, crop choice and land productivity." Noragric Report. no. 55, Ås, Norway: Department of International Environment and Development Studies (Noragric), Norwegian University of Life Sciences (UMB).

Jayne, T.S., Mason, N.M., Burke, W.J. and Ariga, J., 2018. Taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy, 75*, pp.1-14.

Jayne, T.S. and Sanchez, P.A., 2021. Agricultural productivity must improve in sub-Saharan Africa. *Science 372(6546)*, pp.1045-1047.

Jayne, T.S., Snapp, S.S., Place, F. and Sitko, N., 2019. Sustainable intensification in an era of rural transformation in Africa. *Global Food Security, 20*, pp. 105-113.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kisasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., and Zougmoré, R., 2013. *Soil Atlas of Africa*. Luxembourg: European Commission, Publications Office of the European Union.

Katengeza, S.P., Holden, S.T. and Fisher, M., 2019. Use of integrated soil fertility management technologies in Malawi: impact of dry spells exposure. *Ecological Economics, 156*, pp.134-152.

Kerr, R.B., Young, S.L., Young, C., Santoso, M.V., Magalasi, M., Entz, M., Lupafya, E., Dakishoni, L., Morrone, V., Wolfe, D. and Snapp, S.S., 2019. Farming for change: developing a participatory curriculum on agroecology, nutrition, climate change and social equity in Malawi and Tanzania. *Agriculture and Human Values, 36(3)*, pp.549-566.

Kopper, S., Jayne, T.S., Snapp, S.S., 2020. Sifting through the weeds: Understanding heterogeneity in fertilizer and labor response in Central Malawi. *Ecological Economics, 169*, 106561

Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M. and Thomas, C.J., 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science, 7(1)*, pp.25-43.

Lunduka, R., Ricker-Gilbert, J. and Fisher, M., 2013. What are the farm-level impacts of Malawi's farm input subsidy program? A critical review. *Agricultural Economics, 44(6)*, pp.563-579.

Messina, J.P., Peter, B. and Snapp, S.S., 2017. Reconsideration of the Malawian Farm Input Subsidy Program. *Nature Plants*, #NPLANTS-16051706B

Mpeketula, P., 2016. "Soil Organic Carbon Dynamics and Mycorrhizal Fungal Diversity in Contrasting Agroecosytems". PhD Dissertation, Crop and Soil Sciences, Michigan State University.

MPTF (Maize Productivity Task Force, Action Group I), 1999. "Validating and strengthening the area-specific fertilizer recommendations for hybrid maize grown by Malawian smallholders: A research report of the results of the nationwide 1997/98 Maize Fertilizer Recommendations Demonstration". Lilongwe: Ministry of Agriculture and Irrigation.

Mulenga, B., A. Wineman, and N. Sitko. 2016. Climate trends and farmers' perceptions of climate change in Zambia. *Environmental Management, 59 (2)*, pp.291-306.

Mungai, L., Messina, J.P. and Snapp, S.S., 2020. Spatial pattern of agricultural productivity trends in Malawi. *Sustainability*, 2020, 12(4), 1313.

Muyanga, M., Nyirenda, Z., Lifeyo, Y. and Burke, W.J., 2020. "The future of smallholder farming in Malawi". MwAPATA Working Paper 20/03. Lilongwe.

Nicholson, S.E., 2017. Climate and climatic variability of rainfall over Eastern Africa. *Reviews of Geophysics, 55*, pp. 590–635.

Peter, B., Messina, J., Raney, A., Principe, R. and Fan, P., 2021. "MSZSI: Multi-Scale Zonal Statistics [AgriClimate] Inventory" [Data set] available at: https://doi.org/10.7910/DVN/M4ZGXP, Harvard Dataverse, V1

Place, F., Barrett, C.B., Freeman, H.A., Ramisch, J.J. and Vanlauwe, B., 2003. Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems. *Food policy, 28(4)*, pp.365-378.

Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J., Goulson, D., Hartley, S., Lampkin, N., Morris, C. and Pierzynski, G., 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability, 1(8)*, pp. 441-446.

Ricker-Gilbert, J. and Jayne, T.S., 2017. Estimating the Enduring Effects of Fertilizer Subsidies on Commercial Fertilizer Demand and Maize Production: Panel Data Evidence from Malawi. *Journal of Agricultural Economics, 68(1)*, pp. 70-97.

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L. and Corbeels, M. 2017., Agro-ecological functions of crop residues under conservation agriculture. A review. *Agronomy for Sustainable Development, 37(4)*, p.26.

Roobroeck, D., Palm, C., Nziguheba, G., Weil, R. and Vanlauwe, B., 2020. Assessing and understanding non-responsiveness of maize and soybean to fertilizer applications in African smallholder farms. *Agriculture, Ecosystems and Environment 305 (2021)*, 107165.

Samberg, L.H., Gerber, J.S., Ramankutty, N., Herrero, M. and West, P.C., 2016. Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters, 11(12)*, p.124010.

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

Sanchez, PA. 2019., *Properties and Management of Soils in the Tropics, Second Edition.* Cambridge University Press, UK.

Scheiterle, L., Haring, V., Birner, R. and Bosch, C., 2019. Soil, striga, or subsidies? Determinants of maize productivity in northern Ghana. *Agricultural Economics 50(4)*, pp. 479-494.

Schneider, U.A., Havlík, P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., Böttcher, H., Skalský, R., Balkovič, J., Sauer, T. and Fritz, S., 2011. Impacts of population growth, economic development, and technical change on global food production and consumption. *Agricultural Systems, 104(2)*, pp.204-215.

Snapp, S.S., 1998. Soil nutrient status of smallholder farms in Malawi. *Communications in Soil Science and Plant Analysis 29*, pp. 2571-2588.

Snapp, S.S., Grabowski, P., Chikowo, R., Smith, A., Anders, E., Sirrine, D., Chimonyo, V. and Bekunda., M., 2018. Maize yield and profitability tradeoffs with social, human and environmental performance: Is sustainable intensification feasible? *Agricultural Systems 162*, pp. 77-88.

Snapp, S.S., Jayne, T.S., Mhango, W., Benson, T. and Ricker-Gilbert, J., 2014. “Maize yield response to nitrogen in Malawi’s smallholder production systems”. Working Paper 9. Malawi Strategy Support Program. IFPRI. Lilongwe.

Snapp, S.S., Chikowo, R., and Ivanyna, M., 2013. “Ecological intensification and farmer-researcher partnerships”. Invited talk at the Symposium on "TransformingProductivity and Incomes of Poor Farm Households in the Developing World” at the American Association for the Advancement of Science, 14-18 February 2013, Boston, MA.

Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Bunderson, W.T., Eash, N.S. and Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. *Field Crops Research 142*, pp. 47–57.

Tully, K., Sullivan, C., Weil, R. and Sanchez, P., 2015. The state of soil degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions. *Sustainability 7*, 6523-6552.

Wang, H., Snapp, S.S., Fisher, M. and Viens, F., 2019. A Bayesian analysis of longitudinal farm surveys in Central Malawi reveals yield determinants and site-specific management strategies. *PLOS One 14, 8*, e0219296.

Wiyo, K. and Feyen, J., 1999. Assessment of the effect of tie-ridging on smallholder maize yields in Malawi. *Agricultural Water Management, 41*, pp. 21-39.

Zhu, Y., Wang, W. and Yao, X., 2012. Estimating leaf nitrogen concentration (LNC) of cereal crops with hyperspectral data. *Hyperspectral Remote Sensing of Vegetation*, pp.187-206.

Methods Annex

To establish an additional baseline for time-series agricultural productivity in Malawi, remote sensing measurements of crop health (i.e., NDVI) were acquired over a 38-year period (1982–2020). NDVI (normalized difference vegetation index) is a ratio of the red and near-infrared wavelengths of light reflected by surfaces (vegetation in this case), which can be attributed to plant cell structure and is used widely as an indicator of crop health or productivity (Tucker 1979). Two satellite systems—NASA MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA AVHRR (Advanced Very-High-Resolution Radiometer)—were used to evaluate time-series NDVI at the country, district, and extension planning area (EPA) scales. MODIS NDVI (MOD13Q1 v006) spans 2000–Present at a 16-day temporal resolution and a spatial resolution of 250-m (Didan, 2015). AVHRR has a temporal range of 1981–Present, a daily temporal resolution, and a spatial resolution of 0.05° (approximately 5-km in Malawi) (Vermote et al., 2014). AVHRR was selected because it is one of the longest-running vegetation-monitoring satellites and matches the temporal scale of the NUE data evaluated here.

All remote sensing data acquisition and geoprocessing was conducted using Google Earth Engine (GEE) (Gorelick et al., 2017). Mean NDVI of each pixel was calculated across January–April of each year to represent crop productivity during the mid to peak growing season (Jayanthi et al., 2013; Vizy et al., 2015). To visualize fine-spatial-resolution trends, the slope of the regression line was calculated and mapped using the Linear Fit function in GEE and is mapped in Figure 2. A country-wide profile and time-series charts of crop productivity were produced by calculating the mean NDVI across agricultural land in Malawi (based on a stratified random sampling of 2000 points). NDVI data were masked to agriculture using a combination of two land-use/land-cover (LULC) products—ESA/UCLouvain GlobCover 2009 land-use/land-cover (LULC) product (Arino et al., 2010); areas delineated as water by Pekel et al. (2016) and areas with forest cover greater than 25% (Hansen et al., 2013) were also masked out., and GFSAD1000 (NASA/USGS Global Food Security-Support Analysis Data) (Arino et al., 2010; Teluguntla et al., 2015). Pixels classified as agricultural land across both LULC products were used as the mask so that errors of commission would be minimized. Time-series production trends (measured via MODIS and AVHRR NDVI) across agricultural land in Malawi are plotted in Figure 2.

Code Availability

The datasets analyzed during the current study and code for extracting data are available in the Harvard Dataverse repository at https://doi.org/10.7910/DVN/M4ZGXP (Peter et al., 2021).

Additonal References:

Arino O., J. Ramos, V. Kalogirou, P. Defourny and F. Achard. GlobCover 2009. ESA Living Planet Symposium, 27 June- 2 July 2010, Bergen, Norway

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau and R. Moore. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment 202*, pp. 18–27.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R. and Kommareddy, A., 2013. *High-resolution global maps of 21st-century forest cover change. science, 342(6160)*, pp.850-853.

Jayanthi, H., Husak, G.J., Funk, C., Magadzire, T., Chavula, A. and Verdin, J.P., 2013. Modeling rain-fed maize vulnerability to droughts using the standardized precipitation index from satellite estimated rainfall—Southern Malawi case study. *International Journal of Disaster Risk Reduction, 4*, pp.71-81.

Pekel, J.F., Cottam, A., Gorelick, N. and Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. *Nature, 540(7633)*, pp.418-422.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment 8(2)*, pp. 127–150.

Teluguntla, P.G., Thenkabail, P.S., Xiong, J., Gumma, M.K., Giri, C., Milesi, C., Ozdogan, M., Congalton, R., Tilton, J., Sankey, T.T. and Massey, R., 2015. Global cropland area database (GCAD) derived from remote sensing in support of food security in the twenty-first century: current achievements and future possibilities. In *Land Resources: Monitoring, Modelling, and Mapping, Remote Sensing Handbook (Vol. 2)*. CRC Press.

Vermote, E., Justice, C., Csiszar, I., Eidenshink, J., Myneni, R., Baret, F., Masuoka, E., Wolfe, R. and Claverie, M., 2014. NOAA Climate Data Record (CDR) of normalized Difference Vegetation Index (NDVI), Version 5. NOAA National Climatic Data Center.

Vizy, E.K., Cook, K.H., Chimphamba, J. and McCusker, B., 2015. Projected changes in Malawi's growing season. *Climate Dynamics, 45(5-6)*, pp.1673-1698.