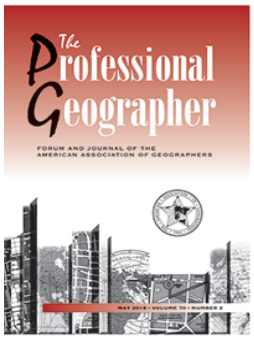

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Scaling Agricultural Innovations: Pigeonpea in Malawi

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Successful scaling of agricultural development strategies is fundamental to increased production and yields, yet targeting efforts frequently fail to fully consider the underlying biophysical drivers of agricultural marginality, particularly at fine spatial resolutions. We present a heuristic for intelligent targeting, utilizing remotely sensed information to identify the intersection between marginal conditions for performance of a staple crop and the optimal niche for technologies that improve crop performance. Here, we explore the geographic potential of maize diversification with pigeonpea, a crop with soil productivity enhancing properties. Overall, 79 percent of agricultural land in Malawi exhibits climate conditions optimal for pigeonpea cultivation and, in total, approximately 51 percent of Malawian maize-based farming is expected to receive some benefit from pigeonpea integration, with 9 percent receiving predictable and substantial benefits. These findings illustrate the geographic scaling potential of pigeonpea in Malawi and provide direction for informed pigeonpea deployment and market development across the country. **Key Words: development, pigeonpea, remote sensing, scaling, targeting.**

农业发展策略的成功尺度化，是生产与产出成长的关键。但瞄准该目标的努力，却经常无法全盘考量农业边缘性的根本生物物理驱力，特别是在细微的空间辨识层次。我们呈现一个智能瞄准的启发式方法，运用遥测信息来指认一种主食作物生产表现的边缘条件与改进作物表现的技术的最佳利基之间的交汇。我们于此探讨玉蜀黍和木豆的多样化栽种之地理潜能，而木豆具有改善土壤生产力的特性。总的来说，马拉威百分之七十九的农业用地展现出对木豆栽种而言的最佳气候条件，而马拉威总共大约有百分之五十一的玉蜀黍栽种，预计将从纳入木豆种植中获得若干益处，而有百分之九将获得可预期的大幅益处。这些研究结果，描绘出木豆在马拉威的地理尺度化之潜力，并且对于全国根据情报的木豆部署与市场发展提供了方向。 **关键词：发展，木豆，遥测，尺度化，瞄准目标。**

La escala de éxito en las estrategias de desarrollo agrícola es fundamental para el aumento de la producción y los productos, aunque los esfuerzos para determinar objetivos con frecuencia fallan en considerar integralmente los controles biofísicos subyacentes de la marginalidad agrícola, en particular cuando se trata de resoluciones espaciales finas. Presentamos una heurística para la inteligente determinación de objetivos, utilizando información de sensores remotos para identificar la intersección entre condiciones marginales para el desempeño de una cosecha esencial y el nicho óptimo para las tecnologías que mejoran el desempeño del cultivo. En el artículo exploramos el potencial geográfico de la diversificación del maíz con el guandul, un cultivo que tiene propiedades fortalecedoras de la productividad del suelo. En general, el 79 por ciento de la tierra agrícola de Malawi exhibe condiciones climáticas óptimas para cultivar guandul y, en total, se espera que aproximadamente el 51 por ciento de la agricultura de Malawi basada en maíz reciba algún beneficio por su integración con el guandul, con un 9 por ciento recibiendo los beneficios predecibles y sustanciales. Estos hallazgos ilustran el potencial de escalamiento geográfico del guandul en Malawi y proveen orientación para el despliegue bien informado del guandul y el desarrollo de su mercado a través del país. **Palabras clave: desarrollo, guandul, percepción remota, escala, determinación de metas.**

In view of widespread food shortages and rural poverty across Africa, scaling innovations to boost agricultural productivity is a global priority and essential to meeting many of the United Nations Millennium Development Goals (Sachs 2005). Although definitions of scaling vary, achieving effective agricultural development involves innovations that have positive impacts on productivity. Scaling in development is both vertical and horizontal. Vertical scaling includes institutionalization or decision making at higher levels and often involves sectors and stakeholder groups in the expansion process (Pachico and Fujisaka 2004). Horizontal scaling, also known as scaling out, refers to geographical spread (Snapp and Heong 2003; Pachico and Fujisaka 2004). In practice, horizontal scaling translates to the widespread spatial adoption of new behaviors or technologies through expansion, replication, and adoption of projects, programs, or policies (Linn 2012). Adoption of new technologies, both inputs and practices, along with the innovative use of existing technologies, is vital to achieving agricultural sector growth. These developments aim to increase land and labor productivity, the effective use of natural resources, and farmer income potential, with market solutions (USAID 2014).

Understanding the drivers that prompt farmers to adopt a new product, process, or practice is an essential part of designing a successful scaling strategy. Adoption is a dynamic process, one that is location specific, and influenced by a wide range of biophysical and socioeconomic factors (Feder, Just, and Zilberman 1985). Not only does technology performance matter, but there is also a need to consider social context, including input and output market opportunities, farmer priorities, and

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perceptions of performance. This is illustrated by adoption and disadoption of drought-tolerant maize varieties by smallholder farmers in Malawi, as nationally representative survey data illustrate that this varies with location, as well as with farmer perceptions of drought risk, and yields of modern maize varieties (Fisher and Snapp 2014). Overall, adoption of sustainable agriculture technologies in Africa has been shown to depend on biophysical performance, which influences profitability, and a complex milieu of land and labor availability, knowledge, extension, technology availability, and policy (Hazell and Wood 2008; Muyanga and Jayne 2014).

Approaches to scaling agricultural productivity commonly address and sometimes mix intensification and extensification. In intensified systems, efforts are made to generate more product on land currently under cultivation. Increasing production is achieved through changes in system inputs (i.e., seed, fertilizer, land, labor, time, or feed; Food and Agriculture Organization of the United Nations [FAO] 2004). Other land-use decisions include the displacement of one commodity for another, where the economic outcome is comparable or greater (Govereh and Jayne 2003). As consideration is given to the importance of agricultural systems in a global context, emphasis is increasingly being given to sustainable intensification practices. Thirty-eight percent of the world's agricultural area has become degraded through poor natural resource management, particularly in Africa, where up to 65 percent of agricultural land suffers from degradation (Feed the Future 2015). With little room to expand agriculture into new areas due to poor suitability, access, or limited availability, there is an increasing focus on intensified agricultural productivity (USAID 2016).

Extensification involves introducing agricultural production into land areas that have been previously unused or used for less intensive purposes (Impact Assessment Group 2000). These land areas are often marginal and might require substantial inputs to bring them into production. High population density and limited land availability, however, is widespread in Malawi, limiting extensification options (Ricker-Gilbert and Jumbe 2014). Between 1990 and 2013, forest cover in Malawi decreased by 23 percent (FAO 2016a), attributed in part to agricultural extensification by smallholder farmers and population increase (Government of Malawi 1998; Chibwana, Jumbe, and Shively 2013). As of 2013, agriculture occupied approximately 61 percent of Malawi's total land area, with forest cover diminishing to 34 percent of the total land area (FAO 2016a). Consequently, options for extensification have been largely reduced to protected or marginal areas, neither of which are viable or sustainable for long-term production demand. Thus, intensification has become the primary focus for soil rehabilitation and increased production.

Prospect for Soil Rehabilitation in Malawi

Malawi is facing recurrent food security crises due in part to long-term unsustainable agricultural practices (Glasson 2010; Mungai et al. 2016). There are other contributing factors, such as historical inequities in resource distribution and minimal investments in infrastructure, research, and education. From a biophysical standpoint, the continuous production of maize over the last several decades has fostered widespread soil nutrient and organic matter degradation (Sanchez 2002; Ngwira, Aune, and Mkwinda 2012; Thierfelder et al. 2013). In the past, emphasis has been placed on fertilizer substitution (e.g., Denning et al. 2009); however, the success and long-term viability of such a solution is widely debated (Chinsinga and Poulton 2014; Messina, Peter, and Snapp 2017), and seemingly ineffective for the rural poor in Malawi (Holden and Lunduka 2013).

Pigeonpea has been proposed as a mitigation strategy for combating soil degradation with its large root system, copious vegetative biomass, and superior ability to fix nitrogen and enhance phosphorus solubilization for soil rehabilitation (Snapp et al. 2010; Ngwira, Aune, and Mkwinda 2012; Mhango, Snapp, and Phiri 2013). The benefits of pigeonpea, grown in combination with maize, or as a doubled-up legume system (i.e., pigeonpea and an understory of soybean or groundnut), rotated with maize, have been proven in country-wide trials (Snapp et al. 2010; Snapp et al. 2014). Perennializing agriculture through growing perennial legumes complementary to existing maize-based farming systems is at the foundation of many such sustainable practices, yet adoption across Africa has been limited (Schulz et al. 2003; Kerr et al. 2007; Snapp et al. 2010). In Malawi, uptake of legume biodiversity is commonly hindered by profitability and farmer preference; however, trials in northern Malawi show promise for semiperennial legume adoption (Snapp et al. 2010).

Pigeonpea is commonly integrated in maize systems in the southern region of Malawi, yet farmers in the northern and central regions have historically elected not to grow pigeonpea, choosing other legumes (e.g., groundnut, soybean, common bean, and cowpea) and other forms of crop diversity (e.g., cassava; Malawi Vulnerability Assessment Committee [VAC] 2005; Simtowe et al. 2010). This regional delineation of crop choice does not appear to be dictated explicitly by biophysical conditions. In terms of temperature and precipitation, 79 percent of southeast Africa (Kenya, Tanzania, Malawi, Mozambique) is suitable for pigeonpea cultivation (Snapp et al. forthcoming). Rather than climate, pigeonpea presence in Malawi might be dictated largely by social factors (e.g., market conditions, culture, extension, labor, preference, or pressure to produce cash crops; Snapp and Silim 2002).

Horizontal Scaling of Pigeonpea in Malawi

Targeting is crucial to the successful deployment and scaling of development strategies and innovation technologies (S. Wood et al. 1999). Although agricultural improvement efforts frequently take place at the local level (e.g., Giller et al. 2006), scaling is typically targeted by region and absent the local context (e.g., Millar and Connell 2010). More regional approaches to scaling agricultural technologies are often unilateral (i.e., focus is given to a singular metric—e.g., sustainability), neglecting to fully address the underlying combinations of biophysical and social factors driving marginality, particularly at fine spatial resolutions. For intervention initiatives to succeed, they need to be delivered in areas where benefits would be substantial and predictable (e.g., biophysical conditions must be considered), and where farmer adoption is realistic (Kwesiga et al. 2003). Here, we focus primarily on the biophysical suitability of pigeonpea across Malawi. This means promoting pigeonpea and encouraging market development in regions and sites where (1) climate conditions are optimal for pigeonpea, and (2) maize suitability and maize production are marginal.

Remotely sensed data offer cost-effective, fine spatial and temporal resolution data to uncover the complex dynamics of agricultural production across the landscape and in remote places on earth. These data allow for intelligent targeting of development strategies beyond administrative levels and beyond often arbitrary decision-making processes unrelated to in situ conditions. Other agricultural improvement initiatives have employed remotely sensed information for targeting deployment of new technologies (e.g., Bellon et al. 2005; Muthoni et al. 2016). Bellon et al. (2005) used remotely sensed climate data in combination with demographic information to target agricultural advancements for poverty alleviation of farmers in Mexico. Muthoni et al. (2016) used a suite of biophysical and socioeconomic variables to recommend zones for sustainable intensification efforts in Tanzania. Our work complements studies such as these and is differentiated by providing a framework to disentangle the complex combinations of the underlying biophysical and possible social factors driving marginality, supplying information and recommendations at a fine spatial resolution, and on a pixel basis. Highlighted here are areas and sites where pigeonpea integration will provide predictable and substantial benefits in a classification format readily usable by policymakers, decision makers, and scholars.

We propose a heuristic for assessing the horizontal scaling potential of pigeonpea in Malawi using a comprehensive suite of remotely sensed measures of agricultural productivity, climate conditions, and land suitability. First, we identify locations where climate conditions are optimal for the cultivation of pigeonpea, based on fundamental niche. Second, we evaluate areas where biophysical conditions for maize are suboptimal and productivity is historically marginal. Finally, the intersection of soil-driven maize marginality and the optimal pigeonpea niche reveals "better bet" locations for predictable and beneficial integration outcomes. We present a range of scaling outcomes and propose areas where pigeonpea will provide positive results based on biophysical suitability, as well as areas that might benefit from extension and market development.

Methods and Data

Pigeonpea Niche

To identify locations suitable for pigeonpea cultivation, we used two remotely sensed products: (1) NASA MODIS Land Surface Temperature (LST—MOD11A2) for temperature (NASA LP DAAC 2015), and (2) NASA/JAXA Tropical Rainfall Measuring Mission (TRMM—3B43) for precipitation (NASA/JAXA TRMM 2016). Thresholds for optimal pigeonpea conditions are based on widely accepted and tested temperature and precipitation ranges (Table 1). We calculated the average value for each pixel across all years under study (2000–2014) for the November through April growing seasons (Jayanthi et al. 2013; FAO 2016b). Only areas where temperature and precipitation were both optimal were considered for the optimal niche.

Targeting Development Strategies

To identify areas where agricultural production is historically poor and soil is likely driving underproduction, we used a Malawi maize suitability map that disaggregates broad classes of suboptimal biophysical conditions and agricultural productivity (Peter, Messina, and Snapp forthcoming). The map depicts all combinations of suboptimal temperature, suboptimal precipitation, soil suitability, and agricultural productivity. The dominant focus here is soil quality and pigeonpea integration. Legumes are generally tolerant to low soil fertility (Snapp and Silim 2002) and are commonly grown in marginal soil environments

Table 1 *Optimal pigeonpea climate niche*

Crop	Temperature (C°)	Precipitation (mm)
Pigeonpea (optimal)[a]	22.7–30.9	544–1,263

Note: Temperature data acquired from NASA MODIS LST (MOD11A2). Precipitation data acquired from NASA/JAXA TRMM (3B43). Precipitation requirements are represented as accumulated growing season rainfall.

[a]L. Wood and Moriniere (2013); Sardana, Sharma, and Sheoran (2010); Valenzuela and Smith (2002); Carberry et al. (2001); Silim and Omanga (2001); Kimani (2001); Omanga, Summerfield, and Qi (1996); Houérou (n.d.).

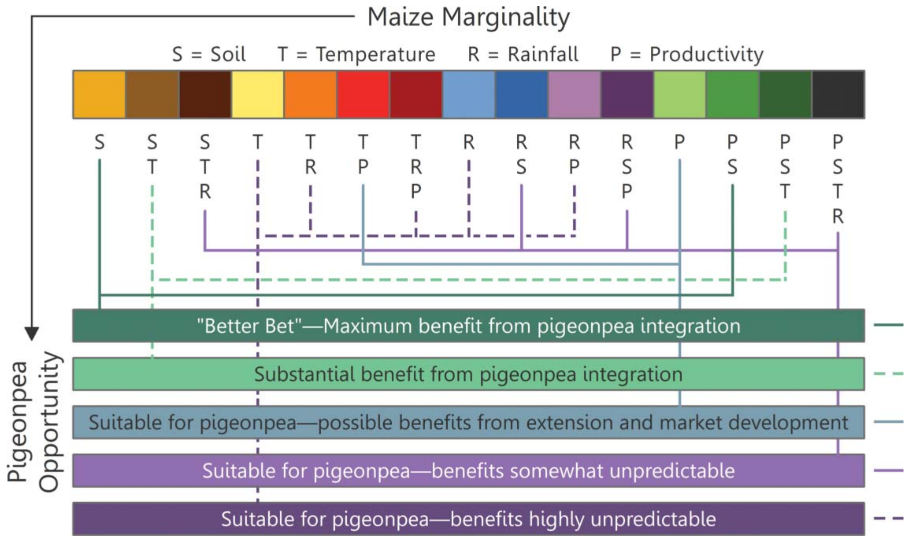

Figure 1 *Reclassification diagram: Transforming maize marginality into pigeonpea opportunity. (Color figure available online.)*

(Kumar Rao and Dart 1987), whereas maize growth is impaired by marginal, resource-poor soils (Heisey and Edmeades 1999). Pigeonpea can grow effectively on marginal soils and its integration with maize cropping systems can provide soil nutrient enrichment, resilience, and improved maize yields (Snapp et al. 2010). Because pigeonpea has these soil rehabilitation properties, a reclassification of the marginal maize map tailored to soil marginality reveals areas where pigeonpea deployment would prove most effective. This reclassification is one that can be easily interpreted and readily used by policymakers and academics to intelligently target research and development scaling initiatives.

Potential areas for pigeonpea deployment are defined as the intersection between soil-driven marginal areas for maize and the optimal climate niche for pigeonpea. Locations where marginality is related to soil (solely or in combination with marginal productivity) were reclassified to a "better bet" option for maximum benefit from pigeonpea integration. In this case, because soil is the only factor (of those under study) driving marginality, positive outcomes from pigeonpea integration are expected. Locations with marginal production, but where low productivity is not explained by any of the explanatory drivers, are areas where marginality might be driven by social factors and would likely benefit from extension and market development. It is also possible, however, that another factor not under study is driving marginality. Marginal productivity and suboptimal temperature regions were also considered potential areas for extension and development.

Other reclassifications include locations that are suitable for pigeonpea, but benefits are somewhat unpredictable because marginality is associated with other factors in combination with soil and might require alternative solutions (e.g., climate-resilient crop varieties). Areas where pigeonpea is suitable, but soil is not a driver of marginality, are classified as highly unpredictable. The following are the resulting categories: (1) Better Bet—maximum benefit from pigeonpea integration; (2) substantial benefit from pigeonpea integration; (3) suitable for pigeonpea—likely benefits from extension or market development; (4) suitable for pigeonpea—benefits somewhat unpredictable; and (5) suitable for pigeonpea—benefits highly unpredictable (Figure 1). The last resulting category (6) includes areas unsuitable for pigeonpea or nonmarginal for maize.

Field Survey and Data Acquisition

In 2015, we conducted a country-wide field survey in which we spoke with extension officers in thirty-three farming regions (extension planning areas [EPAs]) across the extent of Malawi. We visited nine EPAs in the north, eight in the south, and sixteen in the central region, conducting interviews and land-cover/land-use assessments at 200 sites. At each site, we inquired about crops grown and cropping system patterns (e.g., sole crop and intercrop). In addition to our interviews, we acquired EPA-level crop production metrics from the Malawi Ministry of Agriculture and Food Security (MoAFS), which covers the years between 2005 and 2012. These data, along with the interviews, allow us to cross-reference reports of regional crop delineation (VAC 2005; Simtowe et al. 2010), as well as reveal the spatial distribution of pigeonpea production and yield at the local scale. Regional and administrative boundaries are presented here for reference (Figure 2).

Results

Spatial Distribution of Pigeonpea in Malawi

Here we present data on pigeonpea production and yield by administrative unit (EPA) across Malawi for

Figure 2 *Study area map highlighting the northern, central, and southern regions of Malawi and the contained districts and extension planning areas.*

2005 and 2012; these years represent the greatest temporal range in the data available. There is a clear regional pattern of pigeonpea presence in the southern region of Malawi (Figure 3). In 2005, the southern region of Malawi produced 92 percent of the national pigeonpea total (compared with less than 1 percent in the north). In 2012, the southern region of Malawi produced 89 percent of the national pigeonpea total (compared with less than 1 percent in the north). For instances where pigeonpea is grown in the northern and central regions, however, yields are comparable to those observed in the south (Figure 4). In 2005, pigeonpea yields in the southern region averaged approximately 430 kg ha^{-1}, and in the northern region, pigeonpea yields averaged approximately 440 kg ha^{-1}. In 2012, pigeonpea yields in the southern region averaged approximately 980 kg ha^{-1}, and in the northern region, pigeonpea yields averaged approximately 700 kg ha^{-1}. Pigeonpea is scarce in the central region; however, in 2005 pigeonpea yields averaged approximately 470 kg ha^{-1} and in 2012 pigeonpea yields averaged approximately 900 kg ha^{-1}. Coinciding with government reports, our field survey shows an overwhelming presence of pigeonpea in the southern region of Malawi. Of our 200 sites visited (in thirty-three farming regions), we were able to confirm pigeonpea cultivation at forty sites. Of these sites, pigeonpea was grown at only three sites in the north, four in the central region, and thirty-three in the south.

Pigeonpea Niche and Deployment Potential

Malawi's climate is highly suitable for the cultivation of pigeonpea. In terms of both temperature and precipitation, 79 percent of agricultural land exhibits climate conditions optimal for pigeonpea growth

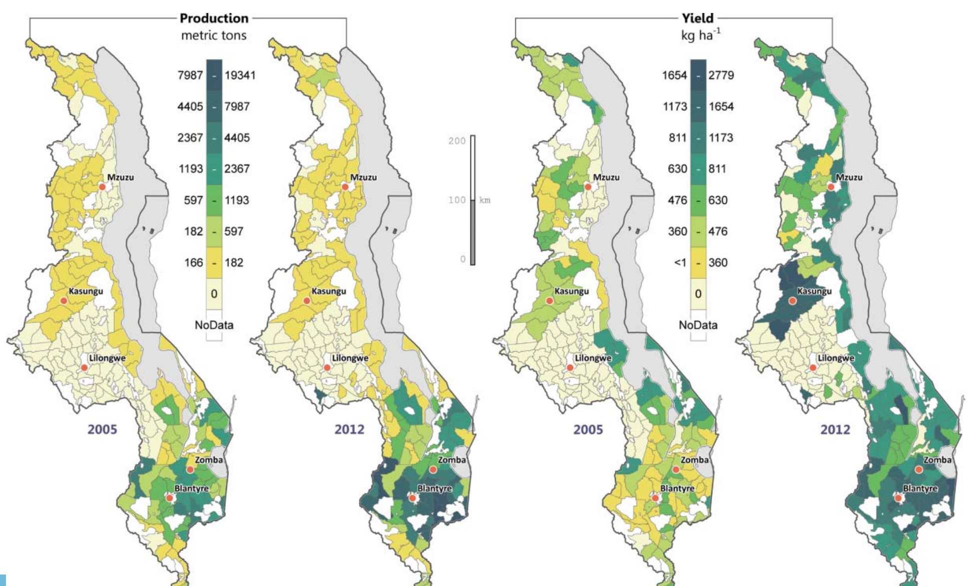

Figure 3 *Map depicts the spatial distribution of pigeonpea production and yield in 2005 and 2012 by extension planning area. (Color figure available online.)*

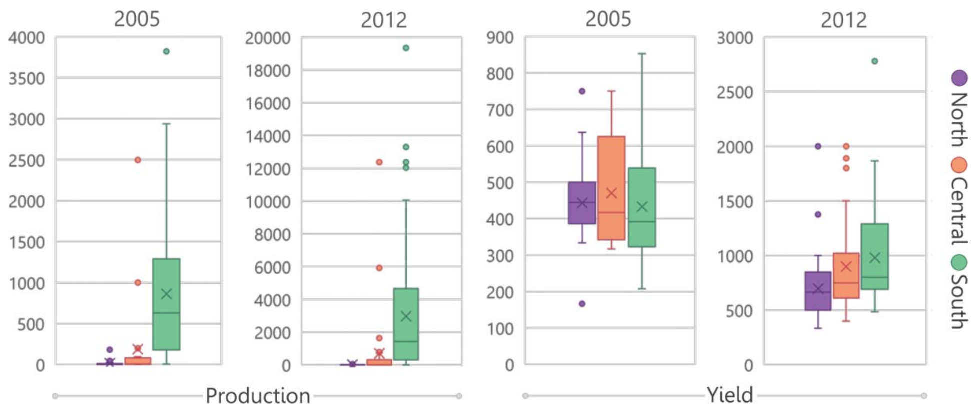

Figure 4 *Regional descriptive statistics: Box and whisker plot of pigeonpea production and yield in three major regional subdivisions of Malawi (north, central, and south) for 2005 and 2012. Production in metric tons and yield in kg ha^{-1}. Note that y-axes vary. (Color figure available online.)*

(Figure 5). Approximately 3 percent is optimal only for temperature and 17 percent is optimal only for precipitation, so only 2 percent of Malawi's agricultural area is entirely suboptimal for pigeonpea.

The intersection of marginal maize and optimal pigeonpea covers 74 percent of agricultural land in Malawi (Figure 6). Within this intersection, 46 percent of maize marginality is attributed to soil (solely or

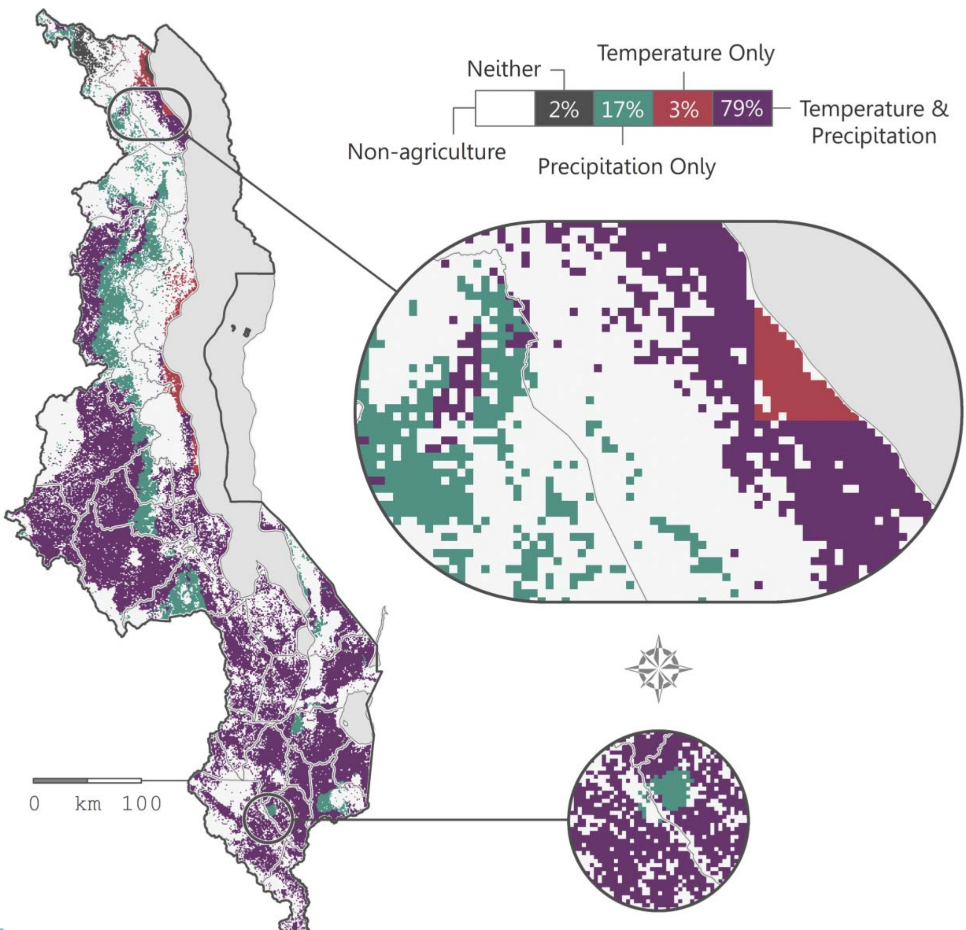

Figure 5 *Pigeonpea climate niche: Optimal temperature and precipitation (2000–2014). Data sources: NASA MODIS LST (MOD11A2) and TRMM (3B43). Inset maps selected to highlight local spatial variability. (Color figure available online.)*

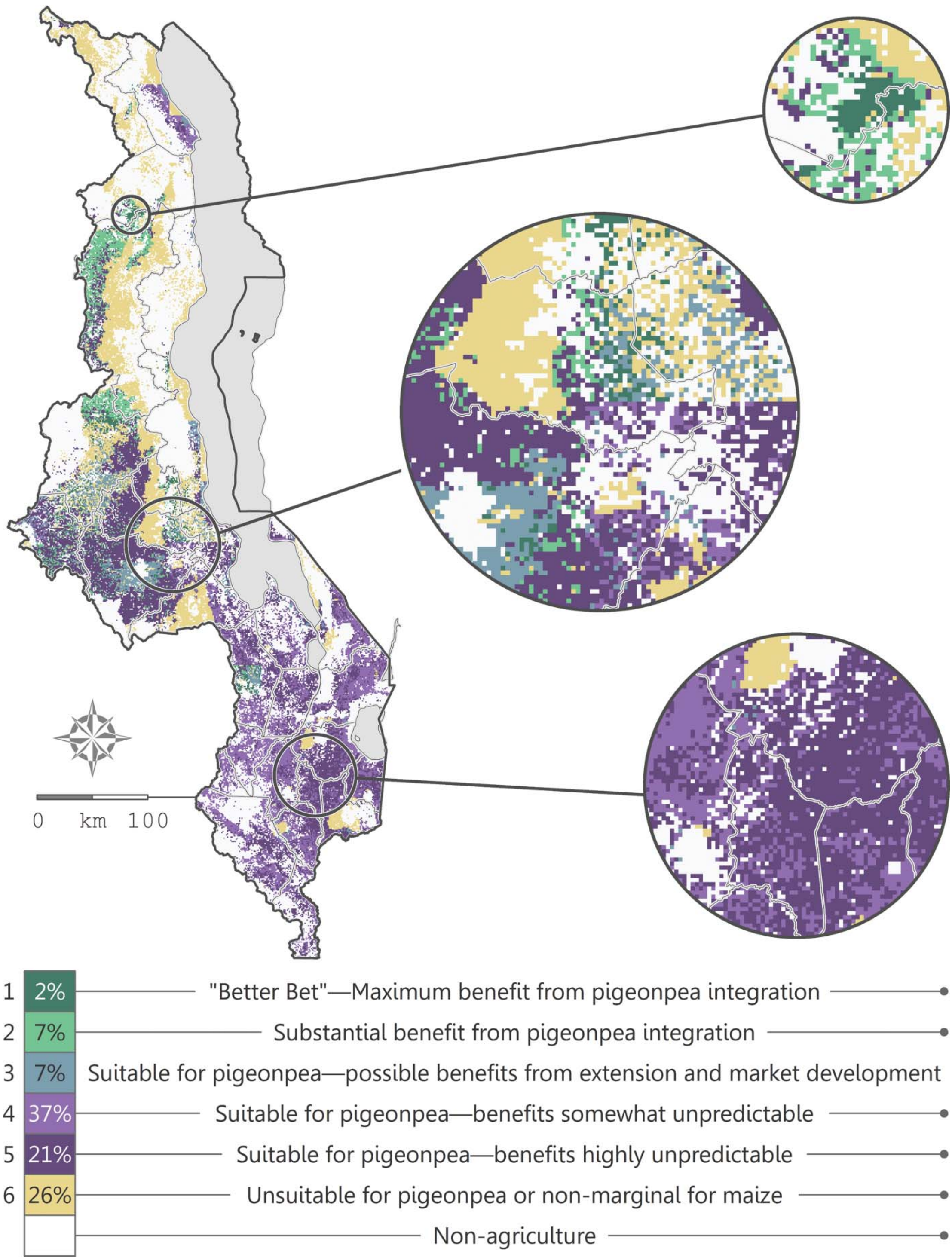

Figure 6 *Potential areas for deployment of pigeonpea and market development. Inset maps selected to highlight local spatial variability. (Color figure available online.)*

in combination with other drivers). Our findings suggest maximum benefit from pigeonpea integration occurring on 2 percent of agricultural land. These are areas where soil suitability is the sole driver of marginality. Seven percent of marginal agricultural land is expected to receive substantial benefit from pigeonpea integration. These are areas where soil suitability is a primary driver of marginality, along with suboptimal temperature conditions. Another 7 percent is suitable for pigeonpea and might benefit from extension and market development. These are areas where productivity is measurably low, yet there is either no observable limiting driver of productivity (of those under study), or temperature is the sole factor. We found that 37 percent of the country is suitable for pigeonpea, but soil is not the sole driver of marginality and benefits are less predictable. Twenty-one percent is suitable for pigeonpea but soil is not a driver of marginal maize; therefore benefits are highly unpredictable. Twenty-six percent is unsuitable for pigeonpea or nonmarginal for maize. Overall, approximately 51 percent of Malawian agriculture is likely to receive benefits from pigeonpea adoption, with varying degrees of predictability and effectiveness, at least 9 percent of which should receive highly predictable and beneficial outcomes from pigeonpea integration.

Discussion

Targeting Investments in Sustainable Agriculture Technologies

It is urgent to reverse the soil degradation trend in Malawi and support sustainable agricultural practices and higher production levels. Agricultural development will not be successful unless sustainable management of the underlying soil resource is addressed, nor will investments in agricultural subsidies achieve profitable returns. To build soil organic matter requires sufficient organic matter inputs, delivered efficiently from leguminous plant roots (Puget and Drinkwater 2001; Kong and Six 2010). In Malawi, sustained effort to improve soil organic carbon is also required. There is a growing body of evidence that the surest way to achieve soil organic matter gains, in a manner that ensures ease of farmer adoption, is to promote crops that are shrubby, such as pigeonpea, in contrast to growing exclusively annual crops that have limited life spans, limited aboveground biomass, and meager root systems (Snapp et al. 2010; Glover, Reganold, and Cox 2012).

Over the long term, technologies such as residue mulch systems, agroforestry, and intensified livestock systems that transfer manure to crop fields are all expected to play a role in building soil productivity in Malawi. Some of these systems, however, have been shown to require substantial labor investments, as well as food production opportunity costs, at least in the short term (Sirrine et al. 2010). The combination of near-term options, such as diversification with pigeonpea, and more long-term, radical options all need to be considered as means to build soil organic matter. This is essential to ensure crop response and profitable use of investments in improved seed and fertilizer. We recommend the Malawi government extension consider innovative approaches to targeting intervention efforts, such as the example presented here that assesses where pigeonpea can be most effectively deployed. To complement long-term investments, we propose immediate research and extension attention be given to multipurpose legumes, such as pigeonpea, in the "better bet" areas we have highlighted.

It is clear that pigeonpea is preferred in the southern region of Malawi, based on the quantity of production; however, in instances where pigeonpea is grown in the northern and central regions, it performs quite well and yields are comparable to those in the south (Figure 4 and Figure 5). These findings support the spatial extent of pigeonpea optimality and the potential for widespread integration (Figure 3). Pigeonpea is largely absent in most of the central region; however, the confirmation of overlapping optimal niche and reported high productivity leads to a reasonable assumption that pigeonpea could be grown successfully in the northern and central region EPAs. In Figure 3, we show that much of the northern region is suitable for pigeonpea, and, based on the drivers of marginality for maize, would receive maximum or substantial benefit from pigeonpea integration. These areas in the northern and central regions are high-priority areas for the scaling and market development of pigeonpea.

Drivers of Pigeonpea Production

This article documents the spatial extent of soil and temperature properties that condition pigeonpea growth and compares this to the actual pigeonpea distribution. It is clear that pigeonpea is underrepresented in terms of biophysical suitability, but is an expanding crop in Malawi. Production area has increased at a rate of about 5.5 percent per year between 2006 and 2014; over the same time period, production has increased at a rate of about 5.6 percent per year, and yield at a rate of about 11.4 percent per year (FAO 2016a). The maps of pigeonpea production and yield presented (MoAFS) are consistent with FAO-reported trends of continually increasing production and productivity in Malawi. Indeed, 2005 was a particularly low producing year due to severe crop response from poorly timed rains (Buerkle 2005); however, there is still a considerable annual yield increase (8.1 percent on average, 2000–2014; FAO 2016a). The maps and reported figures also demonstrate that pigeonpea responds similarly to rainfall stress across regions. Somewhat surprisingly, this rapid upward production and yield trend holds true for many of Malawi's primary crops (e.g., maize, rice, groundnut, soybean, and tobacco). Despite reported production and yield gains across crops, the fact remains that widespread food insecurity persists throughout rural Malawi (Messina, Peter, and Snapp 2017).

A driving factor of increasing pigeonpea production might be the growing international market opportunities occasioned by large and consistent pigeonpea import demands from the Indian subcontinent (Simtowe et al. 2010). Emergent pigeonpea success in neighboring Mozambique and Tanzania (Walker et al. 2015) make it increasingly important for Malawi to situate itself within the pigeonpea export arena. There is somewhat contradictory evidence regarding market demand, which appears to be highly variable in Malawi, as several reports have highlighted farmer concerns with pigeonpea market access limitations outside of southern Malawi (Rogé et al. 2016; Waldman et al. 2017). The central region of Malawi, where the country capital of Lilongwe is situated, is largely undiversified, with maize and tobacco dominating the agricultural landscape (VAC 2005), and pigeonpea is largely absent (Snapp et al. 2003). Conversely, southern districts such as Zomba have a market structure that encourages pigeonpea production and integration (Ortega et al. 2016; Waldman et al. 2016). In Malawi, variability of the pigeonpea market over space and time might drive increased production in some areas and years, and limit it in others, with an overall positive impact on pigeonpea production. Socioeconomic contexts (e.g., market structure and farmer preference) are impeding pigeonpea scaling across much of Malawi. Another barrier to pigeonpea production is the extent of free-ranging livestock in northern and central Malawi. Compared to southern Malawi, there are few community norms that ensure year-round livestock control, which is key to growth and survival of long-lived semiperennial crops such as pigeonpea (Rogé et al. 2016). Taken together, this is suggestive that agricultural development efforts that involve pigeonpea promotion will need to pay attention to livestock control and market policies, as well as biophysical suitability for pigeonpea.

Conclusions

Maize produced in optimal areas with recurring high yields will never be replaced by pigeonpea—the calorie yield difference is simply too great. The strengths of the model proposed here, however, lie in its ability to transform marginality into opportunity with predictable outcomes. Smallholder farmers are generally risk averse. Here, we provide evidence that pigeonpea is a promising and scalable option for soil rehabilitation, nitrogen fixation, and improved maize yields across many specific locations in Malawi. The maps and methodology herein are resources that might be used to intelligently target locations in need of intervention, where benefits will meet expectations and minimize risk. The fine spatial and temporal resolution data we employ allow policymakers and decision makers to focus efforts beyond the regional level, removing some uncertainty in extension delivery and promotion of new practices. Although we focus on maize and pigeonpea here, the model is not limited to a particular crop and could be generalized across geographies, crops, scales, and innovation strategies. Reclassifying the underlying drivers of marginality, tailored to specific technologies, will allow for a wide array of potential for agricultural innovations to scale and improve agricultural systems across Malawi. ■

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Literature Cited

Bellon, M. R., D. Hodson, D. Bergvinson, D. Beck, E. Martinez-Romero, and Y. Montoya. 2005. Targeting agricultural research to benefit poor farmers: Relating poverty mapping to maize environments in Mexico. *Food Policy* 30 (5–6): 476–92.

Buerkle, T. 2005. Malawi facing serious food crisis. FAONewsroom. Rome, Italy: Food and Agriculture Organization of the United Nations. http://www.fao.org/Newsroom/en/news/2005/107298/index.html (last accessed 23 November 2016).

Carberry, P., R. Ranganathan, L. Reddy, Y. Chauhan, and M. Robertson. 2001. Predicting growth and development of pigeonpea: Flowering response to photoperiod. *Field Crops Research* 69 (2): 151–62.

Chibwana, C., C. B. L. Jumbe, and G. Shively. 2013. Agricultural subsidies and forest clearing in Malawi. *Environmental Conservation* 40 (1): 60–70.

Chinsinga, B., and C. Poulton. 2014. Beyond technocratic debates: The significance and transience of political incentives in the Malawi Farm Input Subsidy Programme (FISP). *Development Policy Review* 32:S123–S150.

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

Feder, G., R. E. Just, and D. Zilberman. 1985. Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change* 33:255–97.

Feed the Future. 2015. Feed the Future Food Security Innovation Center: Sustainable intensification. https://feedthefuture.gov/resource/feed-future-food-security-innovation-center-sustainable-intensification (last accessed 18 July 2017).

Fisher, M., and S. S. Snapp. 2014. Can adoption of modern maize help smallholder farmers manage drought risk? Evidence from southern Malawi. *Experimental Agriculture* 50:533–48.

Food and Agriculture Organization of the United Nations (FAO). 2004. The ethics of sustainable agricultural intensification. ftp://ftp.fao.org/docrep/fao/007/j0902e/j0902e00.pdf (last accessed 3 November 2016).

———. 2016a. FAOSTAT database: Input. Land. http://faostat.fao.org/beta/en/#data/RL (last accessed 3 November 2016).

———. 2016b. GIEWS country briefs—Malawi. Global Information and Early Warning System (GIEWS). http://www.fao.org/giews/countrybrief/country.jsp?code = MWI (last accessed 23 November 2016).

Giller, K. E., E. C. Rowe, N. de Ridder, and H. van Keulen. 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems* 88 (1): 8–27.

Glasson, G. E. 2010. Developing a sustainable agricultural curriculum in Malawi: Reconciling a colonial legacy with indigenous knowledge and practices. *Cultural Studies of Science Education* 3:151–64.

Glover, J. D., J. P. Reganold, and C. M. Cox. 2012. Agriculture: Plant perennials to save Africa's soils. *Nature* 489:359–61.

Govereh, J., and T. S. Jayne. 2003. Cash cropping and food crop productivity: Synergies or trade-offs? *Agricultural Economics* 28 (1): 39–50.

Government of Malawi. 1998. *State of the environment report for Malawi*. Lilongwe, Malawi: Environmental Affairs Department.

Hazell, P., and S. Wood. 2008. Drivers of change in global agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1491): 495–515.

Heisey, P. W., and G. O. Edmeades. 1999. *Maize production in drought-stressed environments: Technical options and research resource allocation. Part 1 of CIMMYT 1997/98 world maize facts and trends*. Mexico D.F.: CIMMYT.

Holden, S., and R. Lunduka. 2013. Who benefit from Malawi's targeted farm input subsidy program? *Forum for Development Studies* 40 (1): 1–25.

Houérou, L. n.d. *Cajanus cajan (L.) Millsp. Grassland species profiles*. Rome, Italy: Food and Agriculture Organization of the United Nations. http://www.fao.org/ag/agp/agpc/doc/gbase/DATA/PF000150.HTM (last accessed 7 November 2016).

Impact Assessment Group. 2000. Impact methods to predict and assess contributions of technology. http://cnrit.tamu.edu/IMPACT/ (last accessed 3 November 2016).

Jayanthi, H., G. Husak, C. Funk, T. Magadzire, A. Chavula, and J. Verdin. 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: 71–81.

Kerr, R. B., S. Snapp, M. Chirwa, L. Shumba, and R. Msachi. 2007. Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil fertility. *Experimental Agriculture* 43 (4): 437–53.

Kimani, P. M. 2001. Pigeonpea breeding: Objectives, experiences, and strategies for Eastern Africa. In *Status and potential of pigeonpea in Eastern and Southern Africa: Proceedings of a regional workshop*, ed. S. N. Silim, G. Mergeai, and P. M. Kimani, 21–32. Gembloux, Belgium: Gembloux Agricultural University.

Kong, A. Y. Y., and J. Six. 2010. Tracing root vs. residue carbon into soils from conventional and alternative cropping systems. *Soil Science Society of America Journal* 74 (4): 1201.

Kumar Rao, J. V. D. K, and P. J. Dart. 1987. Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan* (L.) Millsp. of different maturity groups. *Plant and Soil* 99 (2): 255–66.

Kwesiga, F., F. K. Akinnifesi, P. L. Mafongoya, M. H. Mcdermott, and A. Agumya. 2003. Agroforestry research and development in southern Africa during the 1990s: Review and challenges ahead. *Agroforestry Systems* 59:173–86.

Linn, J. F., ed. 2012. Scaling up in agriculture, rural development, and nutrition. International Food Policy Research Institute (IFPRI) Focus 19. Washington, DC: IFPRI.

Malawi Vulnerability Assessment Committee (VAC). 2005. Malawi baseline livelihood profiles: Version 1. http://pdf.usaid.gov/pdf_docs/Pnadg538.pdf (last accessed 3 November 2016).

Messina, J. P., B. G. Peter, and S. S. Snapp. 2017. Re-evaluating the Malawian Farm Input Subsidy Programme. *Nature Plants* 3:17013.

Mhango, W. G., S. S. Snapp, and G. Y. K. Phiri. 2013. Opportunities and constraints to legume diversification for sustainable maize production on smallholder farms in Malawi. *Renewable Agriculture and Food Systems* 28:234–44.

Millar, J., and J. Connell. 2010. Strategies for scaling out impacts from agricultural systems change: The case of forages and livestock production in Laos. *Agriculture and Human Values* 27 (2): 213–25.

Mungai, L., S. S. Snapp, J. P. Messina, R. Chikowo, A. Smith, E. Anders, R. B. Richardson, and G. Li. 2016. Smallholder farms and the potential for sustainable intensification. *Frontiers in Plant Science* 7:1720.

Muthoni, F. K., H. Sseguya, M. Bekunda, and I. Hoeschle-Zeledon. 2016. Identifying recommendation domains for scaling improved crop varieties in Tanzania. Paper presented at the ICT4D Conference, 16–19 May, Nairobi, Kenya.

Muyanga, M., and T. S. Jayne. 2014. Effects of rising rural population density on smallholder agriculture in Kenya. *Food Policy* 48:98–113.

NASA LP DAAC. 2015. MODIS land surface temperature (MOD11A2) version 005 *NASA* EOSDIS land processes DAAC. Sioux Falls, SD: USGS Earth Resources Observation and Science (EROS) Center. https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod11a2 (last accessed 11 November 2016).

NASA/JAXA Tropical Rainfall Measuring Mission Project (TRMM). 2016. TRMM Product 3b43 Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC). http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B43_readme.shtml (last accessed 11 November 2016).

Ngwira, A. R., J. B. Aune, and S. Mkwinda. 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research* 132:149–57.

Omanga, P. A., R. J. Summerfield, and A. Qi. 1996. Flowering in pigeonpea (Cajanus cajan) in Kenya: Responses of medium- and late-maturing genotypes to location and date of sowing. *Experimental Agriculture* 32:111–28.

Ortega, D. L., K. B. Waldman, R. B. Richardson, D. C. Clay, and S. Snapp. 2016. Sustainable intensification and farmer preferences for crop system attributes: Evidence from Malawi's central and southern regions. *World Development* 87:139–51.

Pachico, D., and S. Fujisaka, eds. 2004. *Scaling up and out: Achieving widespread impact through agricultural research*. Cali, Colombia: CIAT.

Peter, B. G., J. P. Messina, and S. S. Snapp. Forthcoming. A multi-scalar approach to mapping marginal agricultural land: Smallholder agriculture in Malawi. *Annals of the American Association of Geographers*.

Puget, P., and L. E. Drinkwater. 2001. Short-term dynamics of root- and shoot-derived carbon from a leguminous green manure. *Soil Science Society of America Journal* 65 (3): 771.

Ricker-Gilbert, J., and C. Jumbe. 2014. How does population density influence agricultural intensification and productivity? Evidence from Malawi. *Food Policy* 48:114–28.

Rogé, P., S. S. Snapp, M. N. Kakwera, L. Mungai, I. Jambo, and B. Peter. 2016. Ratooning and perennial staple crops in Malawi: A review. *Agronomy for Sustainable Development* 36:50.

Sachs, J. 2005. *Investing in development: A practical plan to achieve the Millennium Development Goals*. New York: United Nations.

Sanchez, P. A. 2002. Soil fertility and hunger in Africa. *Science* 295:5562.

Sardana, V., P. Sharma, and P. Sheoran. 2010. Growth and production of pulses. In *Soils, plant growth and crop production*, ed. W. H. Verheye, vol. 3, 378–416. Oxford, UK: UNESCO-EOLSS.

Schulz, S., A. N. Honlonkou, R. J. Carsky, V. M. Manyong, and B. D. Oyewole. 2003. Alternatives to mucuna for soil fertility management in southern Benin: Farmer perception and use of traditional and exotic grain legumes. *Experimental Agriculture* 39:S0014479703001273.

Silim, S., and P. Omanga. 2001. The response of short-duration pigeonpea lines to variation in temperature under field conditions in Kenya. *Field Crops Research* 72 (2): 97–108.

Simtowe, F., S. Asfaw, B. Shiferaw, M. Siambi, E. Monyo, G. Muricho, T. Abate, S. Silim, NVPR, G. Rao, and O. Madzonga. 2010. Socioeconomic assessment of pigeonpea and groundnut production conditions—Farmer technology choice, market linkages, institutions and poverty in rural Malawi. International Crops Research Institute for the Semi-Arid Tropics Research Report No. 6. Hyderabad, India: ICRISAT.

Sirrine, D., C. Shennan, S. S. Snapp, G. Kanyama-Phiri, and B. Kamanga. 2010. Agroforestry risk and vulnerability in southern Malawi: Improving recommendations resulting from on-farm research. *International Journal of Agricultural Sustainability* 8:290–304.

Snapp, S. S., M. J. Blackie, R. A. Gilbert, R. Bezner-Kerr, and G. Y. Kanyama-Phiri. 2010. Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences (PNAS)* 107:20840–45.

Snapp, S. S., and K. L. Heong. 2003. Scaling up: Participatory research and extension to reach more farmers. In *Uniting science and participation: Managing natural resources for sustainable livelihoods*, ed. B. Pound, S. S. Snapp, C. McDougal, and A. Braun, 67–87. London: Earthscan.

Snapp, S., T. S. Jayne, W. Mhango, T. Benson, and J. Ricker-Gilbert. 2014. Maize yield response to nitrogen in Malawi's smallholder production systems. Malawi Strategy Support Program, Working Paper 9. Washington, DC: ICRISAT.

Snapp, S. S., R. B. Jones, E. M. Minja, J. Rusike, and S. N. Silim. 2003. Pigeon pea for Africa: A versatile vegetable—And more. *HortScience* 38 (6): 1073–79.

Snapp, S., P. Roge, P. Okori, R. Chikowo, B. Peter, and J. Messina. Forthcoming. Perennial grains for Africa: A pipedream or an overlooked option? *Experimental Agriculture*.

Snapp, S. S., and S. N. Silim. 2002. Farmer preferences and legume intensification for low nutrient environments. *Plant and Soil* 245 (1): 181–92.

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

USAID. 2014. Scaling up the adoption and use of agricultural technologies. Paper presented at the Global Learning and Evidence Exchange (GLEE). Bangkok, Thailand. https://agrilinks.org/sites/default/files/resource/files/ScalingUpAgTechGLEEReportThailand2014_0.pdf (last accessed 3 November 2016).

———. 2016. Sustainable agriculture: Agriculture and food security. https://www.usaid.gov/what-we-do/agriculture-and-food-security/investing-sustainable-agriculture (last accessed 3 November 2016).

Valenzuela, H., and J. Smith. 2002. Pigeonpea. College of Tropical Agriculture and Human Resources (CTAHR), University of Hawai'i at, Manoa, HI.

Waldman, K. B., D. L. Ortega, R. B. Richardson, D. C. Clay, and S. S. Snapp. 2016. Preferences for legume attributes in maize-legume cropping systems in Malawi. *Food Security* 8 (6): 1087–99.

Waldman, K. B., D. L. Ortega, R. B. Richardson, and S. S. Snapp. 2017. Estimating demand for perennial pigeon pea in Malawi using choice experiments. *Ecological Economics* 131:222–30.

Walker, T., S. Silim, B. Cunguara, C. Donovan, P. P. Rao, M. Amane, and M. Siambi. 2015. Pigeonpea in Mozambique: An emerging success story of crop expansion in smallholder agriculture. Working Paper 78E. Maputo, Mozambique: Ministry of Agriculture and Food Security, Directorate of Economics.

Wood, L., and L. Moriniere. 2013. Malawi climate change vulnerability assessment: Annex D. Crop phenology. African and Latin American Resilience to Climate Change (ARCC). Publication produced for the United States Agency for International Development by Tetra Tech ARD, through a Task Order under the Prosperity, Livelihoods, and Conserving Ecosystems (PLACE) Indefinite Quantity Contract Core Task Order (USAID Contract No. AID-EPP-I-00-06-00008, Order Number AID-OAA-TO-11-00064).

Wood, S., K. Sebastian, F. Nachtergaele, D. Nielsen, and A. Dai. 1999. Spatial aspects of the design and targeting of agricultural development strategies. International Food Policy Research Institute (IFPRI) EPTD Discussion Paper 44. Washington, DC: IFPRI.

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