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Nature-based agricultural solutions: Scaling perennial grains across Africa

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ABSTRACT

Modern plant breeding tends to focus on maximizing yield, with one of the most ubiquitous implementations being shorter-duration crop varieties. It is indisputable that these breeding efforts have resulted in greater yields in ideal circumstances; however, many farmed locations across Africa suffer from one or more conditions that limit the efficacy of modern short-duration hybrids. In view of global change and increased necessity for intensification, perennial grains and long-duration varieties offer a nature-based solution for improving farm productivity and smallholder livelihoods in suboptimal agricultural areas. Specific conditions where perennial grains should be considered include locations where biophysical and social constraints reduce agricultural system efficiency, and where conditions are optimal for crop growth. Using a time-series of remotely-sensed data, we locate the marginal agricultural lands of Africa, identifying suboptimal temperature and precipitation conditions for the dominant crop, i.e., maize, as well as optimal climate conditions for two perennial grains, pigeonpea and sorghum. We propose that perennial grains offer a lower impact, sustainable nature-based solution to this subset of climatic drivers of marginality. Using spatial analytic methods and satellite-derived climate information, we demonstrate the scalability of perennial pigeonpea and sorghum across Africa. As a nature-based solution, we argue that perennial grains offer smallholder farmers of marginal lands a sustainable solution for enhancing resilience and minimizing risk in confronting global change, while mitigating social and edaphic drivers of low and variable production.

1. Introduction

1.1. Adapting agriculture in view of a changing landscape

Globally, there is a call to increase food production through sustainable practices, to counter the effects of climate change, rising population, land-use change, and deterioration of natural resources (Postel, 2000; Godfray et al., 2010). Subsistence agriculture in Africa in particular is becoming increasingly stressed by population pressures, soil exhaustion, and climate change. Since the 1990's, the population of Africa has been growing at a rate faster than the global average (Reilly and Schimmelpfennig, 1999), contributing to the conversion of land for both agricultural production and urbanization. Climate variability, such as unpredictable timing and quantity of rainfall, affect smallholder farmer crop production and farm management practices (Nelson et al., 2009), particularly in marginal environments (Reilly and Schimmelpfennig, 1999). These changes, among others, have prompted increased research for agricultural intensification (Josephson et al., 2014; Ricker-Gilbert et al., 2014). Sub-Saharan African agricultural systems are among the most vulnerable systems facing these challenges (Challinor et al., 2007), and ongoing research that is both innovative and participatory will foster biodiversity and increased productivity (Snapp et al., 2010).

1.2. Sustainable land management and emergent nature-based solutions

Sustainable land management is at the foundation of societal goals to produce food, fuel, and fodder in an environmentally sound and supportable manner over the long-term. How to achieve sustainable intensified agriculture is contested, with advocates promoting such various approaches as organic agriculture, agroecology, and conservation farming (Petersen and Snapp, 2015). At the same time, there are a number of sustainability principles about which consensus is emerging that can be followed regardless of the type of agriculture deployed (Robertson et al., 2014). Notable among these is the case for perennial vegetation (Pimentel et al., 1986; Glover et al., 2010). This type of plant trait ensures greater capture and conservation of resources, as living plants are continuously present to photosynthesize and foster biological

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processes such as nutrient recycling (Jackson, 2002). Thus, a range of alternative management practices, including organic and conservation agriculture can potentially derive considerable benefit from integration of perennials. In contrast, agriculture as currently practiced involves crops with overwhelmingly annual growth habits. This leads to managed lands left bare or unproductive for much of the year, as most food crops are grown for a scant four to five months (Jackson, 2002). There are sustainable alternatives to such annual-intensive production, which include mixed cropping systems that incorporate perennial plants as companion species and the development and deployment of crop plants that have perennial properties. Sorghum and pigeonpea are two such crops with perennial growth habits that allow regrowth and multiple harvests through an agronomic practice called ratooning (Rogé et al., 2016), which involves cutting the main stem(s) after reproductive maturity.

Based on agroecology and conservation agriculture principles, nature-based solutions offer sustainable qualities, such as resilience to disturbance over variable time scales and minimal input requirements, as well as an aim toward general improved human well-being (European Commission, 2015). Nature-based solutions for sustainable urbanization emerged in the European Union as a research initiative with the explicit aim of addressing environmental, social, and economic challenges sustainably (European Commission, 2015). Similarly, smallholder agricultural systems will benefit from adoption of technologies that support sustainable principles and the complex system processes of nature. At the same time, the "net benefit of nature-based solutions depends on how much non-renewable energy can be replaced without decreasing total production of ecosystem services" (Maes and Jacobs, 2015: 3). Attention to resilience and resource amelioration is often overlooked in agricultural discourse in favor of the intensification of high-yield annuals, which dominates the development lexicon. In contrast to nature-based solutions that focus on economic solutions (e.g., fertilizer subsidy), nature-based solutions might be better expressed in the smallholder agricultural context through sustainable soil management strategies, field/crop organization, and local market development.

1.3. Perennial grains: a nature-based approach for Africa

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) is a perennial leguminous shrub commonly cultivated and consumed by smallholder farmers in the tropical and often marginal environments of Africa (Kumar Rao and Dart, 1987). Pigeonpea is biologically suited to production as an intercrop, as a slow initial growth habit minimizes competition for resources with a primary crop (Sakala et al., 2000). Farmers typically grow pigeonpea as a mixed cropping system, producing two or more food products while simultaneously building soil fertility through biological processes (e.g., nitrogen fixation and carbon sequestration) (Fujita et al., 1992; Snapp et al., 2010). Sorghum (*Sorghum bicolor* (L.) Moench) is a grass with perennial properties commonly grown by smallholder farmers in semi-arid regions of Africa (Doggett, 1988; Paterson et al., 2009). The cultivation of sorghum occurs primarily in dryland areas and hot, semi-arid tropical environments (Dicko et al., 2006), though there are sorghum species that grow in wetter regions (Harlan and Stemler, 1976). Sorghum has deep and spread roots and a solid stem (Buchanan, 1885), and it is common to grow sorghum along field ridges, as this helps prevent soil erosion (Okigbo and Greenland, 1976). Pigeonpea and sorghum are generally drought-tolerant and resilient in dryland environments, and in perennial forms maintain these desirable traits (Parr et al., 1990).

A research gap that has not been addressed is the spatial assessment of suitability for diversification of nature-based solutions. In this paper, we consider the phenology of two perennial crops, pigeonpea and sorghum, both of which offer soil rehabilitation properties and are tolerant to marginal environments (Okigbo and Greenland, 1976; Snapp et al., 2010). The unique properties of these crops enhance sustainability of cropping, however they face biophysical constraints and require an appropriate socio-economic context to achieve successful adoption. Our overall objective is to identify appropriate integration properties and delineate the climate niche for deployment of these sustainable perennials within existing maize-based smallholder farms. From an agroclimatology perspective, we explore areas suitable for the cultivation of perennial sorghum and pigeonpea, and highlight the geographic potential for perennial grains to scale across Africa. Remotely-sensed imagery such as those presented here allow for global observation of the environmental and biophysical factors that influence perennial development and adaptation and their spatial organization. Identifying biogeographic conditions in which sorghum and pigeonpea can prosper is crucial for effective integration and scaling of these perennial grains (Wood et al., 1999).

This work builds on other global and continental suitability maps (e.g., the Global Agro-Ecological Zones (GAEZ) database (IIASA/FAO, 2012)) by highlighting the intersection between marginal dominant crop conditions (in this case maize) and optimal perennial crop conditions (in this case pigeonpea and sorghum), ultimately targeting areas where maize-based systems are likely to benefit from perennial integration. More, the data presented here are unaltered and at the remote sensing pixel level, providing a direct link to the farmer experience and offering a level of transparency (in terms of background variables) commonly masked by data aggregations and complex zoning classifications. We use geospatial technologies and techniques to (1) explore suitable (and optimal) climate conditions for pigeonpea and sorghum across Africa, (2) assess marginal maize conditions and historic agricultural productivity, and (3) identify areas where existing maize-based agricultural systems are likely to benefit from integration of sorghum or pigeonpea.

2. Methods

2.1. Fundamental climate niche: maize, pigeonpea, and sorghum

The methodology presented here consists of three major components. First, we identify the fundamental climate niches for maize, pigeonpea, and sorghum. Second, we present a range of suitability (and optimality) for each crop based on temperature and precipitation conditions. Third, we locate the intersection between marginal maize areas and the optimal pigeonpea or sorghum climate niche.

The fundamental climate niche (i.e., temperature and precipitation) used for maize, pigeonpea, and sorghum is based on a literature review of tested crop performance (Table 1). Pigeonpea is tolerant to variable rainfall, from very low to high amounts ranging from 350 to 2000 mm during a growing season (Kimani, 2000; Valenzuela and Smith, 2002; Wood and Moriniere, 2013; Houérou, n.d.), and produces grain even during dry spells, unlike other legumes (Okiror, 1986). The crop prefers temperatures ranging between 20.0 °C and 35.5 °C (Omanga et al., 1996; Carberry et al., 2001; Silim and Omanga, 2001; Sardana et al., 2010; Wood and Moriniere, 2013). Suitable growing season conditions for sorghum consist of rainfall between 150 and 950 mm (Chipanshi et al., 2003; Du Plessis, 2008; Mishra et al., 2008; Wood and Moriniere,

Table 1
Optimal temperature and precipitation ranges for maize, pigeonpea, and sorghum.
Sources: *(Pingali, 2001; Wood and Moriniere, 2013; Sanchez et al., 2014; Infonet, 2016; FAO, n.d.-b). **(Omanga et al., 1996; Kimani, 2000; Carberry et al., 2001; Silim and Omanga, 2001; Valenzuela and Smith, 2002; Sardana et al., 2010; Wood and Moriniere, 2013; Houérou, n.d.). ***(Chipanshi et al., 2003; Du Plessis, 2008; Mishra et al., 2008; Wood and Moriniere 2013; FAO, n.d.-a)

Crop	Temperature (°C)	Precipitation (mm)
Maize*	23.8–32.2	750–1217
Pigeonpea**	22.7–30.9	544–1263
Sorghum***	22.1–33.7	317–833