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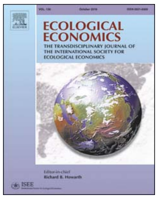

Analysis

# Adaptation to Climate Change in Rainfed Agriculture in the Global South: Soil Biodiversity as Natural Insurance

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ABSTRACT

Increased drought frequency in many parts of the world, especially in the global South, is expected due to accelerating climate change. We present a bioeconomic model that unpacks the role of soil biodiversity as contributing to both increasing and stabilizing agricultural productivity in low-input rainfed farming systems. The natural insurance value of soil biodiversity mostly depends on farmers' risk preferences as well as on the frequency of drought events to be insured against. We show that when the probability of drought increases, soil biodiversity conservation can be an optimal ecosystem-based adaptation strategy. However, this is only likely to be the case up to a given drought probability threshold. The natural insurance value of soil biodiversity for climate change adaptation in drought prone rainfed agricultural systems depends on a combination of key hydrological, agronomic and economic parameters.

## 1. Introduction

In many parts of the global South, especially in sub-Saharan Africa (SSA), agricultural production is largely rainfed. Actually, < 5% of agricultural land in SSA is equipped for irrigation and large disparities are observed between countries (FAO, 2014). Rainfed agriculture in SSA is specially exposed to climate variability (Niang and Ruppel, 2014). Decrease in annual rainfall coupled with more frequent drought episodes has been observed over the past 30 years (Funk et al., 2008; Williams and Funk, 2011) and climate variability is expected to increase significantly in the region (Cooper et al., 2008; Niang and Ruppel, 2014). In this climatic context, significant crop yield losses are likely to occur (Roudier et al., 2011), putting the most vulnerable small scale farmers' food security at risk (Challinor et al., 2007; Niang and Ruppel, 2014; Schmidhuber and Tubiello, 2007).

Infrastructural investments in 'blue water' (from lakes or rivers) for agricultural systems in SSA is limited for several reasons, including financial constraints for large scale expansion of irrigation schemes (Rogers et al., 2002) and associated high transaction costs (Kadigi et al., 2012; Rosegrant and Cline, 2003), increased concerns about the environmental impacts of irrigation (Smakhtin, 2002); and also, the limited access of farmers to markets. In this context, investments in 'green water', i.e. water from precipitation and made available to plants in the soil, could reduce the risk of dry spells and drought locally (Falkenmark and Rockström, 2008). This is an ecosystem based strategy to manage soil ecosystems to improve adaptation to increased rainfall variability (Bewket, 2007; Biazin et al., 2012; Rockström et al., 2010). However, agroecologically based practices such as those involved in *conservation agriculture* (Hobbs et al., 2008; Pittelkow et al., 2014) also imply some costs to farmers (Giller et al., 2009).

Agricultural biodiversity is a complex and integral component of *conservation agriculture*, supporting multiple ecosystem functions and intermediate ecosystem services essential for agricultural productivity (Brussaard, 1997; Tscharntke et al., 2012) and food security (Pascual et al., 2011, 2013). It has been suggested that ecosystems with higher levels of biodiversity tend to use biotic and abiotic resources more effectively than less diverse ones and are more productive and stable (Turnbull et al., 2013). In soils, soil biota is important for soil productivity (Barrios, 2007; Hector and Bagchi, 2007), have complex interactions with aboveground biodiversity (De Deyn and Van der Putten, 2005), and impact hydrological pathways (Bardgett et al., 2001) and biogeochemical processes in the nutrient cycle (Swift et al., 2004). For example, Spurgeon et al. (2013) found in a meta-analysis that the abundance and complexity of fungal and earthworms impact soil structure stability and water infiltration rates. Species interact in a complex way; where soil macro fauna and earthworms, in particular,

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transform organic matter and facilitates and accelerate its decomposition by bacteria and fungi (Nielsen et al., 2011). Beyond the idea of species richness, an important hypothesis in ecology is that species are functionally redundant, and thus as a species may be lost in a system, another can take its place in terms of providing the same function (Bengtsson, 1998).[1] Nielsen et al. (2011) have examined the functional redundancy hypothesis of soil biodiversity for carbon cycling. They found that both community composition and species richness influence carbon cycling. The role of species diversity within functional groups is thus important in soil ecology. In our approach, we use a standard definition of soil biodiversity as “the variation of soil life, from genes to communities, and the ecological complexes of which they are part, that is from micro-habitats to landscapes” (Turbé et al., 2010).

The capacity of biodiversity to enhance the flow of ecosystem services and their stability has been conceptualized as the natural insurance value of biodiversity for risk averse users of ecosystem services (Baumgärtner, 2007); soil biodiversity thus confers to ecosystem users an insurance against the variability of income.[2] Identifying the productive and insurance values of soil biodiversity are seen as an important step to understand the role of soil biodiversity conservation in climate change adaptation (Pascual et al., 2015). The studies focusing explicitly on the role of biodiversity from a farmer's perspective have been mostly concerned with plant biodiversity, focused on crop productivity (Chavas and Falco, 2012) and income variability (Di Falco and Chavas, 2008; Finger and Buchmann, 2015). To date studies focused on soil biodiversity from a farmer's perspective are theoretical contributions that analyze the notion of the value of agrobiodiversity at large (Baumgärtner and Quaas, 2010; Omer et al., 2010; Pascual et al., 2013) or on the productive value of soil biota (Foudi, 2012). There is thus a scant literature that integrates economic considerations into the viability of soil ecosystem-based approaches for sustainable agricultural intensification or/and climate smart agriculture. Here we use a theoretical bioeconomic model to fill this gap.

The insurance value is highly dependent upon the ecosystem properties, economic context and the risk preferences of users, and can be subjected to non-linearities and threshold effects (Baumgärtner and Strunz, 2014). Soil biodiversity has mainly an indirect value, as it influences intermediate ecosystem services such as water regulation via soil functions on water cycling (Pascual et al., 2015). To analyze some potential thresholds under which soil biodiversity conservation can help to manage soil moisture and lead to potential increase and a stabilization of crop production, we make the (intermediate) soil hydro-ecosystem service explicit via a production function approach. The model is particularly suitable for studying vulnerable small-holder farming systems, such as those associated with rainfed agriculture in SSA. Our model captures basic ecological-economic links between soil biodiversity, hydrological processes and small-scale farm economy under climate variability proxied by changes in the quantity of expected rainfall. Under such climatic variability, the management of soil moisture via soil biodiversity is seen as a key approach, mediated by farmers' risk preferences.[3] The model contributes to the understanding of the risk reducing properties of soil biodiversity from a farmers' perspective and helps to determine economically optimal soil conservation strategies in agroecosystems that rely on rainfall and that are not capitalized except via human and natural capital, such as those used by millions of smallholders in the global South. It highlights under which social-ecological conditions soil biodiversity conservation is seen as natural insurance against of rainfall variability.

The next section presents the basic building blocks of the bioeconomic model and establishes how soil biodiversity influences the mean and variance of agricultural production. Section 3 determines the economic optimal conservation strategy of a representative risk averse small-scale farmer, typical of rainfed agriculture in SSA, with soil biodiversity being the main mechanism to regulate soil moisture. The next section focuses on the impact of increased drought frequency on the farmers' optimal strategy towards soil biodiversity conservation. Finally, the last section concludes and offers some additional insights to enrich the current policy discourse on climate smart agriculture.

## 2. The Bioeconomic Model

We consider a rainfed farming system, typical of most of SSA, where rainfall is the only source of water for agricultural production. We assume soil biodiversity to be a stock of natural capital (Brock et al., 2009) which enables the supply of intermediate water regulation services in terms of water accumulation potential and water storage capacity, which in turn supports food production as a final ecosystem service (Pascual et al., 2015) or regulate nature's contribution to people (NCP) (Pascual et al., 2017). We first describe the hydrological-agronomic submodel and then the economic submodel, as components of the bioeconomic model.

### 2.1. The Hydrological-Agronomic Model

Given that the rainfall pattern is a central feature of rainfed agriculture, without loss of generality, we assume two stochastic rainfall periods or key rainfall events during a given agricultural season. For each event/period a low level of rainfall, denoted $\pi_l$ or a high level of rainfall, $\pi_h$, occurs with probability $\varphi_l$ and $\varphi_h = 1 - \varphi_l$, respectively. Rainfall is then assumed to be absorbed by the soil prior to be used by plants for transpiration.

Different soil organisms play complementary roles in determining the fundamental characteristics of the soil, soil structure and soil texture (Altieri, 1999). This partly determines the way water infiltrates into the soil and the way water is retained. For example, organisms such as earthworms affect soil permeability while smaller organisms tend to have a greater impact on soil porosity by gradually breaking down the soil components and therefore affecting the soil's capacity to withhold water (Edwards and Arancon, 2004; Gupta and Larson, 1979; Hudson, 1994). Following Allison (1973) and Bastardie et al. (2005), we therefore assume that the higher the diversity of soil organisms, the more likely it is that soil has a higher capacity to store water, as represented by Eq. (1):

$$S_c = L \times [I_b]^{\mu} \tag{1}$$

where $S_c$ is the soil's water storage capacity, $L$ is a proportionality coefficient, $I_b$ is the stock of soil biodiversity and μ is a parameter between 0 and 1. Eq. (1) also states that soil biodiversity increases the water storage capacity at a decreasing rate.[4] To describe the dynamics of water in the soil, we use a modified version of *Darcy's law*[5] that describes the infiltration of water in a porous medium (Kirkham, 2005). The flow of water in the soil is described by a difference equation as a function of the total quantity of water in the porous medium and the intrinsic properties of the medium (Roscoe, 1968). Eq. (2) adapts Darcy's law in a simple way:

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[1] Functional redundancy occurs if multiple species share a trait that enhances ecosystem functioning. The chance of adding a species with a trait not observed in the community becomes smaller as species richness increases.

[2] In this approach, the insurance value of soil biodiversity is measured as a change in the risk premium due to a marginal change of biodiversity.

[3] The elicitation of risk aversion has a long history in agricultural economics (Antle, 1987; Just and Pope, 1979; Lence, 2009) and its impact on policy is an active discussion topic (Just and Peterson, 2010; Just, 2008; Just and Just, 2011).

[4] The incremental species enhances soil storage capacity by different mechanisms but the possibility to bring additional water holding capacity is limited because of the intrinsic properties of the soil (Jhonson, 2009) and because of the functional redundancy of additional species.

[5] Darcy's law is a simplification of the more general Richard's law that represents water flow in non-saturated soils.