Agricultural Systems 129 (2014) 30–39

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Managing soil natural capital: An effective strategy for mitigating future agricultural risks?

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ARTICLE INFO

Article history:
Received 29 November 2013
Received in revised form 18 April 2014
Accepted 6 May 2014
Available online 2 June 2014

Keywords:
Soil ecosystem services
Copula model
Dynamic portfolio theory
Soil organic carbon
Sustainable agriculture
Resilience

ABSTRACT

Uncontrollable events such as adverse weather and volatile prices present considerable risks for arable farmers. Soil natural capital, which views the capacity of soil biodiversity to generate ecosystem services as a component of farm capital, could be important for the stability and resilience of arable production systems. We investigate therefore whether managing soil natural capital could be an effective strategy for mitigating future agricultural risks. We do this by constructing a dynamic stochastic portfolio model to optimize the stock of soil organic carbon (SOC)—our indicator of soil natural capital—when considering both the risks and returns from farming. SOC is controlled via the spatial and temporal allocation of cash crops and an illustrative replenishing land use. We find that higher soil natural capital buffers yield variance against adverse weather and reduces reliance on external inputs. Managing soil natural capital has therefore the potential to mitigate two serious agricultural risks: energy price shocks and adverse weather events, both of which are likely to be exacerbated in the future due to, e.g., globalization and climate change.

1. Introduction

Consideration of risks is pivotal for farmers when making agricultural management decisions (Chavas and Holt, 1990; Leathers and Quiggin, 1991). The major risks confronted are production risk due to uncontrollable events such as adverse weather or attacks by pests and pathogens, and market risk due to uncertainty about future input and output prices (Pannell et al., 2000; Moschini and Hennessy, 2001). Adverse weather events such as drought, excessive moisture, hail, frost and flooding account for a high proportion of yield losses (Vergara et al., 2008). Arguably the capacity to adapt to weather variation will be increasingly important for farmers in the face of climate change (Wall and Smit, 2005). Further, farmers all over the world are becoming increasingly exposed to volatile global markets. Seasonal variation in input and output prices can be predictable but much price variation is dependent on unforeseeable shocks to both supply and demand (de Janvry and Sadoulet, 2010; Derek, 2011) or on variation in the quality of products (Hueth and Ligon, 1999; Larsen and Asche, 2011).

The most common methods used by farmers to mitigate risks are crop diversification (e.g., cultivating more than one crop at the same time) and risk sharing through the purchase of financial instruments (Jain and Parshad, 2006). Crop diversification requires low correlation between crop prices or yield responses to weather events and has in this sense similarities to choosing a portfolio of securities (Markowitz, 1959; Di Falco and Perrings, 2005). Farmers can also share risks with others by purchasing financial instruments, e.g., the Federal Crop Insurance Program in the USA (Goodwin et al., 2004; Vedenov and Barnett, 2004), forward and future contracts and options. Forwards and futures can be used to fix the selling price at a specified date, whereas an option gives the farmers the right, but not the obligation, to sell their output at a reference price and date (Tomek and Peterson, 2001).

A less understood possibility is the role *soil organisms* and associated ecosystem services—what we mean by *soil natural capital* (Sukhdev et al., 2010; Kareiva et al., 2011), henceforth soil capital—play in the control of agricultural risks. In natural ecosystems the soil functions as a dynamic regulator whereby species-rich organism communities (or soil biodiversity) influence the magnitude and temporal distribution of carbon and nutrients, particularly

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http://dx.doi.org/10.1016/j.agsy.2014.05.003
0308-521X/

nitrogen and phosphorous, and hence the prospects for plant growth under different weather conditions. In contrast, in intensive farming systems less reliance is placed on the soils' capacity for self-regulation and greater dependence is placed on inputs and management (Swift et al., 2004). Despite this trend, even the most intensively farmed arable soils still house complex biological communities that generate a wide range of supporting and regulating *ecosystem services* that underpin agricultural productivity, particularly: nutrient cycling, nitrogen fixation, phosphorus acquisition, decomposition of organic materials-mineralization of carbon, soil structure modification, moisture regulation, and pest and disease control (Altieri, 1999; Barrios, 2007). These ecosystem services tend to be degraded over time if conservation measures are not taken (Bommarco et al., 2013).

Managing soil natural capital might therefore be an additional method to mitigate production risk as higher abundances and diversity of soil organisms increases both the generation and reliability of soil ecosystem services (Koellner and Schmitz, 2006). It might also reduce market risk because ecosystem services can substitute for costly inputs such as inorganic fertilizers, pesticides and energy (Thrupp, 2000; Weitzman, 2000; Figge, 2004). Knowledge is however lacking about the potential of soil capital to reduce agricultural risks (Brussaard et al., 2007), rather the focus of research has been on top-soil conservation and its expected economic benefits (Burt, 1981; Goetz, 1997; Pretty et al., 2011; Bommarco et al., 2013; Paul et al., 2013). Here we investigate whether managing soil natural capital, as represented by the stock of soil organic carbon (SOC), can mitigate multiple agricultural risks.

Relations between soil organisms and their ecosystem services (ES) are complex and knowledge of the links between them is sparse (Bardgett et al., 2005; de Vries et al., 2013). For this reason, an approximation of soil capital is necessary for informing management decisions. It is widely accepted that SOC is a major factor in a soil's overall health and agricultural productivity (Johnston et al., 2009; Lal, 2010). This is because the utilization of soil organic matter as a substrate of energy by soil organisms underpins the generation of soil ecosystem services (Bauer and Black, 1994) and, consequently, loss of organic carbon will diminish a soil's capacity to generate services. The carbon content of a soil is also related to the size, complexity and functioning of soil food webs (de Ruiter et al., 2005). Therefore a change in SOC content can be used as a proxy for changing stocks of soil capital.

Although soil capital has the potential to reduce agricultural risks, there are few studies that actually evaluate it (Schläpfer et al., 2002; Koellner and Schmitz, 2006), and none in respect of arable farming. Di Falco and Perrings (2005) and Di Falco and Chavas (2008, 2012) studied how spatial crop diversity could be used to mitigate agricultural risk. Our article goes beyond spatial diversification (and crop rotations generally) by incorporating the role of soil capital, which is affected by farming choices over time, in reducing agricultural risk exposure. Consequently, while a static approach is sufficient for analyzing the crop diversification problem our analysis requires a dynamic model to link past cropping decisions to the current stock of SOC.

On the other hand, there is an extensive literature that applies modern portfolio theory to the crop diversification problem (Moschini and Hennessy, 2001; Nalley and Barkley, 2010; Rădulescu et al., 2011). The first application goes back to Freund (1956) who measured the risk of an agricultural enterprise as the variance of its returns, hence showing quadratic programming could be used for determining optimal crop allocations incorporating risk. Hazell (1971) changed the risk measure of farm returns to the mean absolute deviation. As a result the crop diversification problem could be formulated as a linear programming problem (Brink and McCarl, 1978). However, in practice the covariance matrix is infeasible to estimate or unknown due to paucity of data;

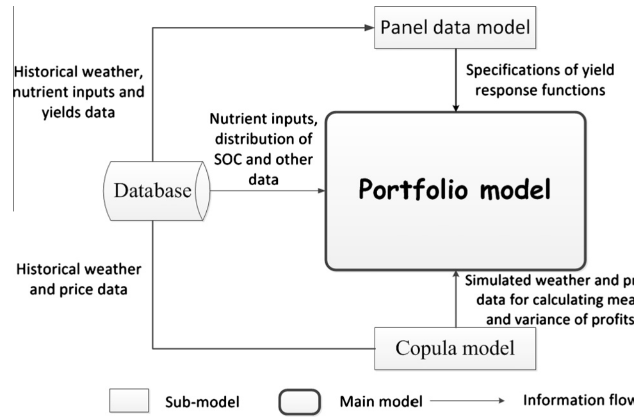

Fig. 1. Flow diagram of the logical relationships among the models and data.

additionally it can only capture linear relationships (Pafka and Kondor, 2003; MacLean et al., 2007). In our study we aim to capture potentially correlated weather and market risks.

Consequently to model the potential for soil capital—a stock variable (i.e., SOC here)—to control agricultural risks a number of innovations are required. First, a Copula method is introduced to model the dependence structures of stochastic weather variables relevant to crop yields (Woodard et al., 2011) and stochastic input and output prices (Serinaldi, 2009; AghaKouchak et al., 2010), which makes it possible to simulate both the expected profit and concomitant risk (via the variance of expected profits) generated by a particular crop portfolio.

Second, we estimate crop production functions (e.g., Frank et al., 1990) that predict crop yields based on fertilizer input, the state of SOC and weather outcomes. Many articles focus on the relationships among yields, nutrient inputs (primarily N, P, and K), and moisture and temperature (Ackello-Ogutu et al., 1985; Malik and Sharma, 1990; Muchow et al., 1990; Halvorson and Reule, 1994), but few address the relationships among yield, SOC and the weather based on yield functions (Lal, 2006; Benbi and Chand, 2007). To predict the effects of changes in soil capital and associated ecosystem services on crop yield, we link crop yield to fertilizer input, the stock of SOC and weather variables by estimating production functions with data from long-term agricultural field experiments (Appendix C). This makes it possible to examine changes in expected yield and its variance given simulated price and weather in the future.

Finally, we extend the traditional static portfolio model to a dynamic setting to analyze the effects of managing (i.e., conserving or depleting) SOC on expected farm profit and risk. The logical relationships among models and data flows are shown in Fig. 1. In the next section we specify the dynamic portfolio model. A numerical case is then analyzed based on data from a typical arable cropping region in northern Europe.

2. The portfolio model

We begin by developing a static portfolio model as a benchmark, after which we extend it to the dynamic setting, with both considering weather and market risks. Consider a farm comprising a set of arable fields $j \in \{1, 2, \ldots, m\}$ that are located within the same climate zone such that all fields are subjected to identical stochastic weather events. The area of field j is S_j (ha). The stock of SOC associated with field j is C_j (% SOC) which is included in the model as a state variable. SOC content is assumed to be homogeneous within each field but can vary among fields. The other variables of the model are: