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Agroforestry versus farm mosaic systems – Comparing land-use efficiency, economic returns and risks under climate change effects

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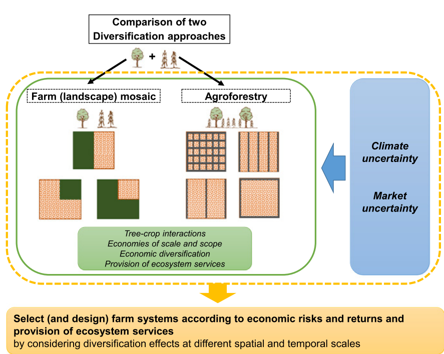
HIGHLIGHTS

- Agroforestry and a farm mosaic diversification approach are compared in terms of economic efficiency.
- The approach accounts for economic and climate uncertainty.
- A process-based growth model is coupled with Modern Portfolio Theory.
- Agroforestry can compete with a farm mosaic system if it allows for beneficial tree-crop interactions and economies of scope.
- Under high risk aversion a farm mosaic diversification system may be preferable.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing land-use conflicts call for the development of land-use systems that reconcile agricultural production with the provisioning of multiple ecosystem services, including climate change mitigation. Agroforestry has been suggested as a global solution to increase land-use efficiency, while reducing environmental impacts and economic risks for farmers. Past research has often focused on comparing tree-crop combinations with agricultural monocultures, but agroforestry has seldom been systematically compared to other forms of land-use diversification, including a farm mosaic. This form of diversification mixes separate parcels of different land uses within the farm. The objective of this study was to develop a modelling approach to compare the performance of the agroforestry and farm mosaic diversification strategies, accounting for tree-crop interaction effects and economic and climate uncertainty. For this purpose, Modern Portfolio Theory and risk simulation were coupled with the process-based biophysical simulation model WaNuLCAS 4.0. For an example application, we used data from a field trial in Panama. The results show that the simulated agroforestry systems (Taungya, alley cropping and border planting) could outperform a farm mosaic approach in terms of cumulative production and return. Considering market and climate uncertainty, agroforestry showed an up to 21% higher economic return at the same risk level (i.e. standard deviation of economic returns). Farm compositions with large shares of land allocated to maize cultivation were also more severely affected by an increasing drought frequency in terms of both risks and returns. Our study demonstrates that agroforestry can be an economically efficient diversification strategy, but only if the design allows for economies of scope, beneficial interactions between trees and crops and higher income

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diversification compared to a farm mosaic. The modelling approach can make an important contribution to support land-use decisions at the farm level and reduce land-use conflicts at the landscape level.

1. Introduction

The sustainable development goals (SDGs) have reinforced the global target of satisfying the needs of a growing world population (target 1 and 2, among others) while reducing the degradation of natural resources (e.g. targets 6, 13, 14, 15). This calls for the development of land-use systems that allow for a sustainable production of food, energy and timber while reducing environmental impacts (Tilman et al., 2011; Godfray and Garnett, 2014; Paul and Knoke, 2015).

In this context, re-integrating trees and tree stands in agriculture-dominated landscapes has been particularly promoted (e.g. Nair and Garrity, 2012). Integrating trees into agricultural landscapes is expected to buffer adverse effects of agriculture on soil resources, enhance the provision of ecosystem services such as carbon sequestration or water retention, create habitats and provide additional and secure income to farmers (Baah-Acheamfour et al., 2016; Lasco et al., 2014; Torralba et al., 2016; Zomer et al., 2016). The latter aspect is especially important in the context of climate change, given the expected increase in agricultural losses due to more frequent extreme weather events (Porter et al., 2014; Harrington et al., 2016). Land-use, and hence product diversification, has been identified as a key mitigation option in the face of climate change (OECD, 2011; Anton et al., 2012) and market uncertainties (Abson et al., 2013; Castro et al., 2015).

The question of exactly how such an integration of trees to diversify farm portfolios should be designed, is still debated. Two major strategies are discussed: 1) the direct mixing of trees and crops on the same piece of land in a spatial or temporal sequence, known as agroforestry (Nair, 1985; Nair and Garrity, 2012b), and 2) a "coarse-level mixing" of trees and crops on separated parcels (Price, 1995) or "compartments" (Odum, 1969) within a farm, which we will refer to as "farm mosaic" (FM) (Fig. 1). For simplicity we use the term "agroforestry" (AF) as a synonym for the direct mixing of trees and crops on the same parcel of land, even though we are aware that "wood lots" or small-scale reforestation are sometimes also classified as agroforestry (Nair, 1985).

Past research has revealed a range of arguments which speak for and against each diversification strategy, FM and AF. An advantage of a FM system is the reduced management complexity and ease of mechanized agricultural management compared to AF, while adverse effects of large-scale monocultures, such as soil erosion, may still be moderated (Odum, 1969; Knoke et al., 2012). FMs have the further advantage that they can avoid competition between species for light, water and soil resources, which may otherwise reduce productivity of individual components (Rao et al., 1997).

However, tree-crop interactions may also increase productivity per unit area, through complementary and supplementary growth effects (Luedeling et al., 2016; Ong et al., 1996; Rao et al., 1997). This increase in land-use efficiency of AF compared to monocultures has been advocated using the Land Equivalent Ratio (LER), introduced by Willey and Rao (1980). The LER compares the yields from growing trees and crops (or multiple crops) together with yields from growing the same components in monocultures. Following Ong (1996), p.6 the LER is interpreted as "the ratio of the area under sole cropping to the area under intercropping, at the same level of management that gives an equal amount of yield". This original concept has been expanded by Peter and Runge-Metzger (1994) to consider multiple crop rotations in time (area-time equivalent ratio) and by Keesman et al. (2011) using advanced biophysical modelling for silvo-arable systems.

While the traditional LER focuses on productivity and excludes any economic considerations, Ranganathan et al. (1991) developed the Yield Advantage Index (YAI), derived from production possibility curves and associated price lines (see Filius, 1982). These approaches are useful to support decisions in annual cropping systems. However, for agroforestry where a perennial tree component is mixed with an annual crop component, these approaches do not adequately account for farmers' preferences to receive money now rather than later, which is usually reflected by a discount rate.

From an economic point of view, increasing the number of products through any land-use diversification strategy may increase per-unit

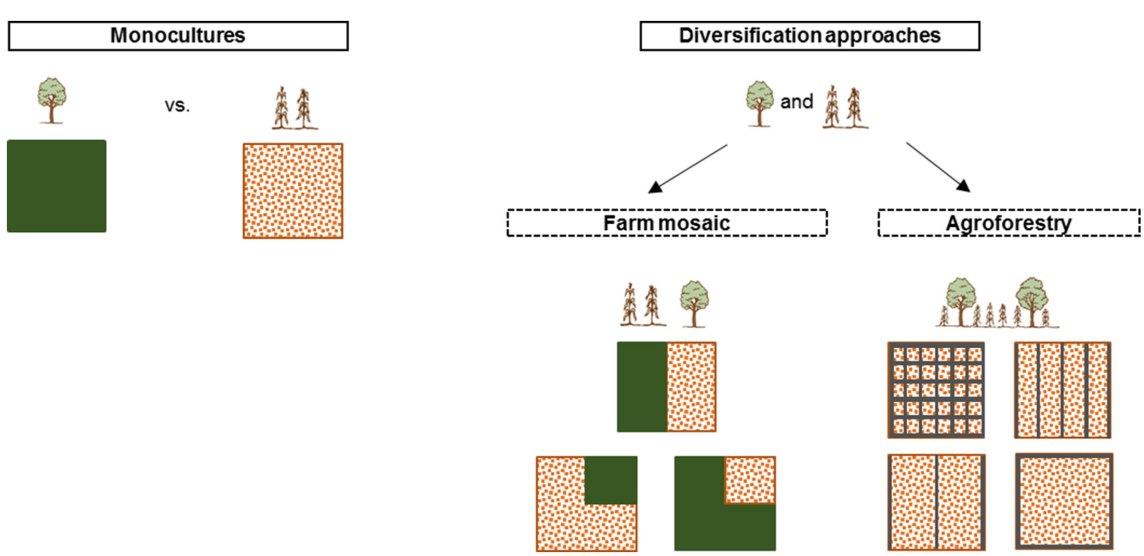

Fig. 1. Schematic representation of farm mosaic and agroforestry diversification approaches as an alternative to farm level monocultures of trees or crops. (Green parcels represent areas planted with trees. Orange areas are covered by crops (or pasture)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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