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Review

On-farm diversity offsets environmental pressures in tropical agro-ecosystems: A synthetic review for cassava-based systems

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ABSTRACT

Ecosystem integrity is at risk across the tropics. In the quest to meet global dietary and market demands, tropical agro-ecosystems face unrelenting agricultural intensification and expansion. Agro-biodiversity can improve ecosystem stability and functioning, but its promotion in smallholder-based systems faces numerous practical hurdles. In the tropics, cassava (*Manihot esculenta* Crantz) is cultivated on over 25 million hectares and features as the third most important source of calories. Cassava crops are often maintained by resource-poor farmers who operate on marginal lands, at the fringes of sensitive, biodiverse habitats. As traditional intercropping schemes are gradually abandoned, monoculture cassava systems face stagnating yields, resource-use inefficiencies and agro-ecosystem degradation. A global literature search identified 189 cassava intercropping studies, covering 330 separate instances of intercropping systems. We employed a vote-counting approach and simple comparative measure across a subset of 95 studies to document the extent to which intercropping sustains a bundle of ecosystem services. Across geographies and biophysical conditions, a broad range of intercrops provided largely positive effects on five key ecosystem services: pest suppression, disease control, land equivalency ratio (LER), and soil and water-related services. Ecosystem services were augmented through the addition of a diverse range of companion crops. Results indicated 25 positive impacts vs. 3 negative impacts with the addition of maize, 5 vs. 1 with gramineous crops, 23 vs. 3 with four species of grain legumes, and 9 vs. 0 with trees. Appropriate intercropping systems can help to strike a balance between farm-level productivity, crop resilience, and environmental health. Our work highlights an urgent need for interdisciplinary research and systems-level approaches to identify intensification scenarios in which crop productivity, provision of ecosystem services, biodiversity conservation, and human well-being are all balanced.

1. Agricultural expansion puts tropical ecosystems at risk

Rapid population growth, shifting consumption patterns, and resource competition are increasing pressure on the world's agricultural systems and non-arable land (Godfray et al., 2010). Contemporary agricultural trends have dramatically shifted farming practices, promoted rapid expansion of agricultural lands, and triggered global environmental changes that risk destabilizing whole ecosystems (Foley et al., 2011). With agro-ecosystems covering 37.5% of global national land surfaces in 2014 (FAOSTAT, 2016), environmental impacts linked to farm-level management decisions are substantial, and are expected to be exceptionally pronounced in tropical terrestrial ecosystems (Laurance et al., 2014a, 2014b).

The pursuit of increased production through both area expansion and farming intensification has resulted in an increase of agricultural areas in the tropics of > 100 million ha in the 1980-90s, occurring largely at the expense of intact or disturbed forests (Gibbs et al., 2010). The limits to this expansion have simultaneously driven a need to increase productivity on limited land, sparking research into the causes of sub-optimal yields and the potential for 'yield gap closure' (van Ittersum et al., 2016; Sayer and Cassman, 2013). Farmers often respond to the need for increased productivity with intensification measures, many of which have negative environmental impacts at field, farm, and agro-landscape levels (e.g., Emmerson et al., 2016). Irrational pesticide and fertilizer use and extractive management are commonplace, leading to soil and water resource degradation in many parts of the tropics (Godfray et al., 2010), while exacerbating biotic and abiotic production constraints in both intensified and low-input farming systems (Poppy et al., 2014).

Millions of smallholder farmers eke out a living by continuously cropping in such settings, which are characterized by shrinking natural resource bases and degraded agro-ecosystem functioning (Bai et al., 2008; Barbier, 1997; Bossio et al., 2010). Though they constitute the backbone of global food security, many of the world's smallholders

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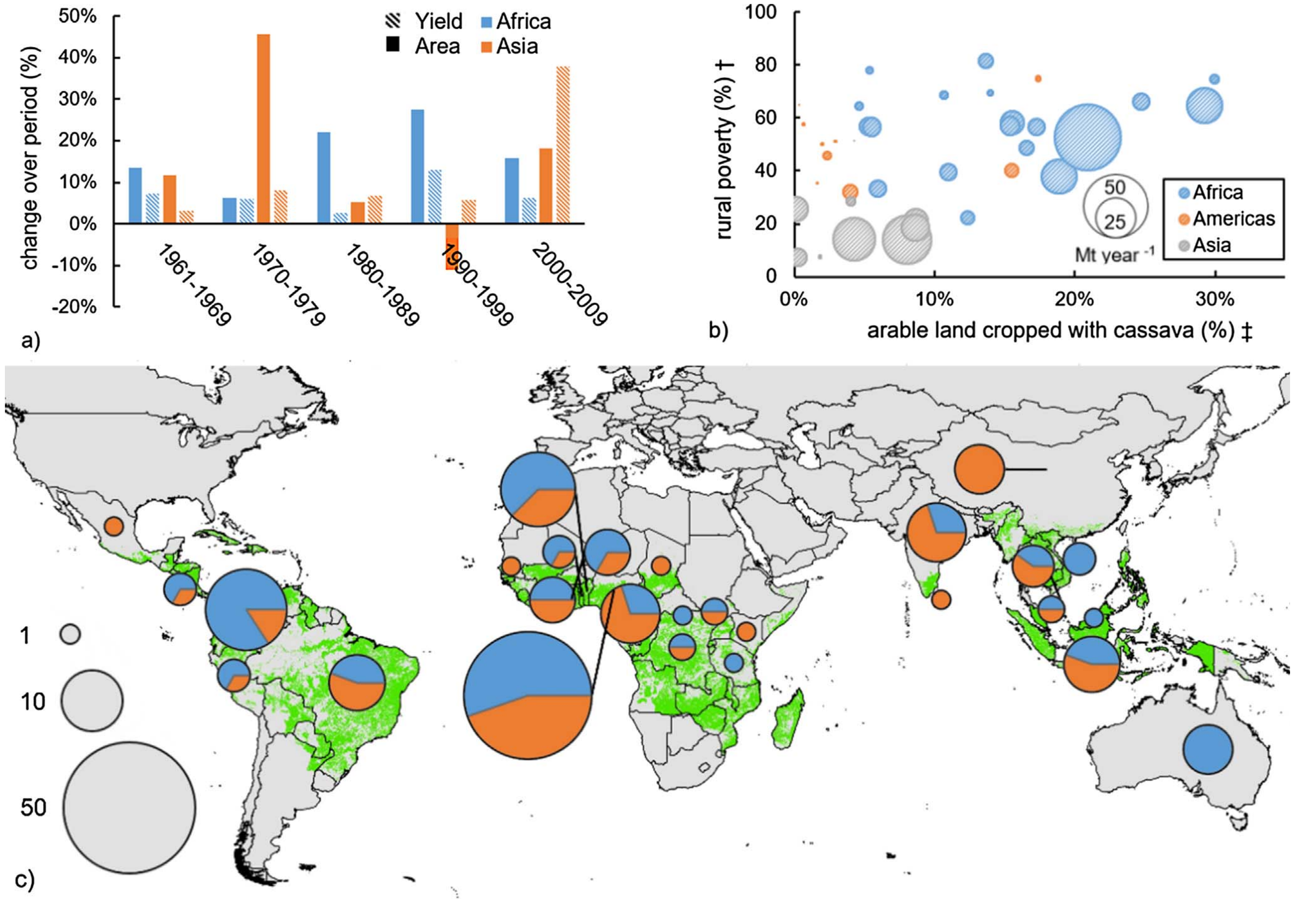

Fig. 1. Trends in cassava production and research: cassava production has intensified over the past 5 decades, both in terms of area and yield (a). Countries across the developing-world tropics have a high degree of dependence on cassava in their agricultural systems and high levels of rural poverty as seen in (b) where each bubble represents a single country (FAOSTAT, 2016). Studies on cassava intercropping originate from a wide geographic area (c). The green backdrop indicates harvested cassava area in 2014 (MAPSPAM, 2016), while bubble size indicates total number of studies and blue segments indicate the proportion selected for final ecosystem services analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

continue to live in poverty, cultivate marginal lands, and operate on the fringes of sensitive, biodiverse habitats (Tscharntke et al., 2012).

In this paper we explore how field-level diversification fosters the provision of multiple key ecosystem services (i.e., soil and water conservation, pest regulation and disease control, and land equivalency ratio) in a major tropical and subtropical food crop. More specifically, we examine the example of intercropping in cassava-based systems through an ecosystem services lens. We provide information on recent trends in cassava cultivation globally, and subsequently discuss associated environmental impacts. Next, we systematically review the literature on intercropping practices in cassava-based systems, present its impacts on multiple ecosystem services, and discuss further implications of these findings for cassava-based farming systems across the tropics.

2. Cassava: an adaptable 'survivor' crop

Cassava (*Manihot esculenta* Crantz) production has increased greatly in the past 50 years (Fig. 1b). This starchy, tuberous staple is now cultivated on ~ 25 million ha throughout the global tropics (FAOSTAT, 2016). Originating in the Neotropics (Olsen and Schaal, 1999), cassava is now an important food in sub-Saharan Africa and South America, while in mainland Southeast Asia it is predominantly a cash crop. Cassava is the largest calorie producer among roots and tubers, making it a critical crop in resource-poor farming settings across the global tropics (Fig. 1b). Cassava is highly adaptable to variable conditions, being grown in a wide range of agro-ecological settings: from Africa's arid Sahel and the cool highlands of Zambia to Colombia's Andean lowlands and the limestone uplands of Laos and Vietnam. A perennial woody plant primarily managed as an annual, cassava is cultivated for its starchy roots used as human food, animal feed, a source of industrial starch, and a biomass energy feedstock (Zhou and Thomson, 2009; von Maltitz et al., 2009).

A hardy 'survivor' crop, cassava thrives in degraded settings, under low soil fertility, at high temperatures, and can withstand periodic droughts (El-Sharkawy, 2014). Cassava is highly resilient and adaptable in the face of ongoing climatic changes, providing options for adaptation in challenging environments (Jarvis et al., 2012). Cassava's ability to grow on poor soils, under sub-optimal climatic conditions, and to provide the advantage of flexible harvest timing, make it the crop of 'last resort' across the tropics (Hillocks et al., 2001) and earn it the moniker 'the drought, war, and famine crop' (Burns et al., 2010).

Because intermediate yields are often attainable even in poor conditions, for example ~ 14T/ha on East and Southern African smallholder farms (Tittonell and Giller, 2013), cassava is often cultivated in monocultures, without proper addition of fertilizer or organic amendments, with complete abandonment of rotation schemes, and using low quality planting material. Cassava enjoys a theoretical yield potential (defined as the yield of a crop grown in the absence of biotic constraints, and with non-limiting water and nutrients) approaching 90 T/ha (Cock et al., 1979; van Ittersum et al., 2016). Despite this, average yields in the tropics remain low, and are increasing only slowly (El-Sharkawy, 2012; Tittonell and Giller, 2013). Farm yields throughout Africa as a whole average 10 T/ha, far below both the 15–40 T/ha