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Productive performance of alternative land covers along aridity gradients: Ecological, agronomic and economic perspectives

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ABSTRACT

The replacement of natural vegetation by pastures and extensive crops is generally driven by economic incentives and supported by technology improvements and multiple subsidies. However, towards areas of increasing aridity the productive performance of these replacements may decline from all perspectives – ecological to agronomic to economic – due to intrinsic differences in the structural and physiological adjustment of natural and cultivated vegetation to reduced and fluctuating water availability. We compare natural woody vegetation, perennial C4 pastures and annual crops (maize, soybean and wheat) along a gradient of decreasing precipitation (900–400 mm of annual mean) encompassing the current agricultural frontier of the Dry Chaco and Western Espinal ecoregions of South America. We assess (i) aboveground net primary productivity (ANPP) (ii) yields of product dry mass, edible energy and protein outputs and, (iii) economic gross profits and return of investment. We linked climatic with yield data from national statistics, field trials and empiric models, together with productive parameters and market prices obtained from local consultants and economic bulletins. Maize achieved the highest ANPP of all vegetation covers (+42% in average compared to the rest) along the entire precipitation gradient, while the rest of the crops were very similar to natural vegetation. Pastures approached the ANPP of natural vegetation in the humid range, but had the lowest performance below 700 mm (−15%). Along the entire precipitation gradient, maize was outstanding in mass and edible energy yield while soybean was so in protein production. Soybean had the highest gross profit per hectare (+50%) and total capital return of investment (+70%). Pastures offered the highest functional capital return of investment (+98%; without fixed capital, infrastructure and land value costs), explaining their relevance at the onset of the deforestation process and the gradual prevalence of crops afterwards. While agronomic and economic incentives for natural vegetation replacement remain strong along the whole aridity gradient, crop choice rather than land use system seem to shape the key ecological process of net primary productivity.

1. Introduction

The replacement of natural vegetation – including forests, savannas and grasslands – with pastures and extensive crops has been the basis for increasing the production and appropriation of ecosystem goods that satisfy human needs (DeFries et al., 2004). The shortage and variability of rain that characterize arid and semiarid ecosystems (Noy-Meir, 1973), which occupy one fifth of terrestrial surface (UNESCO, 1977), have limited this replacement process due to high risks of productive failure of cropped systems in the short term, and higher degradation rates in longer terms (Foley et al., 2005). However, increases in the global demand of agricultural products (Alexandratos, 1999), the development of new soil and water management practices together with crop breeding and genetic modifications (Ahmad et al., 2012; Rockström, 2004; Sadras and Roget, 2004) and facilitated access to remote areas (Pfaff, 1999) strongly incentives current and prospective expansion in arid and semiarid regions (MEA, 2005).

These incentives for the replacement of natural vegetation involve complex tradeoffs that integrate a hierarchy of ecological, agronomic, and economic perspectives of the alternative land use systems (Kareiva et al., 2007), which can change from humid to arid conditions. From the ecological perspective, one of the most relevant issues is to what extent cultivation undermine the process of biomass production,

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due to its intrinsic link with goods yield and other essential services of nature (Fisher et al., 2009). Opposite aspects may prevail depending on the intensity and length of water deficits: (i) the adaptive advantages of the natural vegetation with higher water use efficiency and stress-tolerance (Bacon, 2004) or (ii) the human-selected advantages of cultivated systems displaying lower respiration costs and responding more effectively to disturbances and subsidies (Begon et al., 2009). Thus, maximum primary production rates will likely be expected for natural vegetation towards drier conditions and for crops towards more humid ones. From the agronomic perspective, the priority is the partition of biomass towards harvestable products as food, fiber and fuel (Haberl et al., 2007). Generally, yield and harvest operations improve in more homogeneous crop structures (Evans, 1996). Since most of primary productivity is mainly used as food for human consumption (Vitousek et al., 1986), edible energy yield, probably followed by protein are the most appreciate quality factors (Drewnowski and Popkin, 1997). Finally from the economic perspective, the monetary benefits and mainly profits margin of resources invested emerge as the ultimate factor for decision makers in market-oriented economies (Gasparri et al., 2013). This fact becomes critical for ecosystem functioning and services as economic results maximization often displaces agriculture toward areas with lower performance from ecological or even agronomic perspectives (Fisher et al. 2009).

Vegetation covers in most populated regions of the world shows a relative dominance of rainfed crops in more humid areas, of pastures or double-purpose crops (fodder/grain) in intermediate conditions, and of natural vegetation towards extreme aridity unless irrigation is applied (Ellis et al., 2010; Grigg, 1974). Ecophysiological contrasts between these types of vegetation covers and their dominant functional type of plants suggest that high rates of photosynthesis and nutrients uptake to plant grow and production are favored in fertile and humid lands (Lambers et al., 1998). Opposedly, slow-grow and stress-tolerant species with more resource-use efficiency, structural tissues and roots tend to be increasingly favored in arid lands (Grime, 2006). Besides, tradeoffs between carbon gain and water loss suggest the presence of optimum ranges of stress intensity for each plant functional types (Solbrig and Orians, 1977). Thus, along a gradient of increasing aridity a sequence of optimum performance for fast growing annuals (crops), intermediately growing perennial grasses and forbs (pastures), and then for slow growing xerophytic woody plants (natural vegetation) can be expected. The result would be a progressive shift in advantages for annual crops, pastures, and natural vegetation, at least in the ecological process of biomass production (Hypothesis 1A - Fig. 1). However, the higher usable fraction and more favorable cost-value relationship of the produced biomass may likely imply advantages from an agronomic and economic perspective for annual crops above all other covers and for pastures above natural vegetation (Hypothesis 2, Fig. 1).

In this work we compared natural woody vegetation and pastures and crops as its replacement, with their corresponding mixed ranching-forestry, ranching and cropping land use systems. We explore the productive performance of these systems linking tradeoffs from three perspectives that range from the basic underlying ecological process of biomass production, to the agronomic process of harvesting goods, to the economic process of profit generation. The set of variables includes magnitude of aboveground net primary production, yield of commercial products (grain, meat, wood and charcoal) in terms of mass and edible energy and proteins, and gross profit and return on investment. These analyses were performed along a gradient of decreasing annual precipitation spanning from 900 to 400 mm, encompassing the two largest semiarid ecoregions of Southern South America, the Dry Chaco and Western Espinal. Diverse data sources were combined, including climate databases, field trials, yield records, empiric biophysical models, together with costs/prices information from local consultants and economic bulletins.

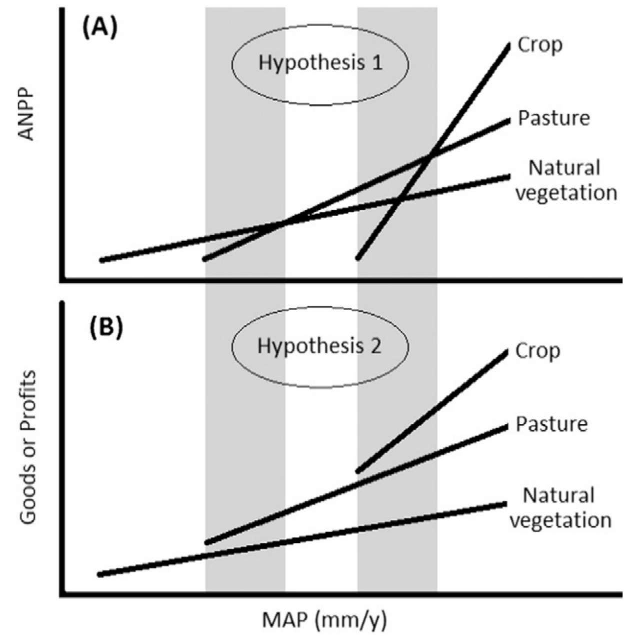

Fig. 1. Hypothesis regarding decreasing mean annual precipitation (MAP) effects on three vegetation covers from the perspective of (A) the ecological process of biomass production, and (B) the agronomic or economic process of goods or profits generation. A higher threshold of minimum MAP for crop vs. pasture cultivation is assumed. Gray zones show hypothetical MAP belts in which agronomic/economic criteria could favor vegetation covers with suboptimal biomass production.

2. Materials and methods

2.1. Study region

We focused our analysis in the semiarid belt of Argentina and Paraguay, which includes approximately 450,000 km^2 of the Dry Chaco and Western Espinal ecoregions, along a precipitation gradient from 900 to 400 mm year^{-1} (Fig. 2). This region is characterized by flat to slightly rolling topography, with predominance of Mollisols and Entisols developed on alluvial and eolian sediments. Predominant natural vegetation includes xerophyte woodlands and shrublands, alternated with transitions to savannas and pure grasslands stands (Cabrera, 1971) and with variable degrees of replacement with pastures and annual crops (Clark et al., 2010; Graesser et al., 2015; Vallejos et al., 2014). Traditionally, natural vegetation was used for cattle ranching, complemented with selective logging of wood for charcoal and others products of low aggregated value (Bucher and Huszar, 1999; Dussart et al., 2011; Karlin et al., 2004; Rueda et al., 2013). These forestry activities are normally characterized by low technology and manual work (Rueda et al., 2015; Turc and Mazzucco, 1998). Alternatively, the establishment of cultivated pastures of megathermal African grasses (C4 photosynthetic syndrome) has been progressively adopted due to their higher forage production and stocking rate capacity (Rueda et al., 2013; Stritzler et al., 2007). Under either natural vegetation or pastures, current ranching systems are characterized by extensive cow-calf activities, where young calves are sold for breeding and fattening in more favorable regions (Garbulsky and Deregibus, 2004; Morris and Ubici, 1996). These activities required infrastructure such as fences and watering points but have low dependence of external inputs (Laca, 2009; Magliano et al., 2015). Most recently, extensive cropping systems (mostly soybean, maize and wheat) expanded throughout the region with a strong commodity export orientation (Leguizamón, 2014), copying the more humid Pampas productive model (highly dependent on machinery and agrochemical inputs) with minor adjustments to local arid conditions (Viglizzo et al., 2011).