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Reevaluating suitability estimates based on dynamics of cropland expansion in the Brazilian Amazon

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ABSTRACT

Agricultural suitability maps are a key input for land use zoning and projections of cropland expansion. Suitability assessments typically consider edaphic conditions, climate, crop characteristics, and sometimes incorporate accessibility to transportation and market infrastructure. However, correct weighting among these disparate factors is challenging, given rapid development of new crop varieties, irrigation, and road networks, as well as changing global demand for agricultural commodities. Here, we compared three independent assessments of cropland suitability to spatial and temporal dynamics of agricultural expansion in the Brazilian state of Mato Grosso during 2001–2012. We found that areas of recent cropland expansion identified using satellite data were generally designated as low to moderate suitability for rainfed crop production. Our analysis highlighted the abrupt nature of suitability boundaries, rather than smooth gradients of agricultural potential, with little additional cropland expansion beyond the extent of the flattest areas (0–2% slope). Satellite-based estimates of the interannual variability in the use of existing crop areas also provided an alternate means to assess suitability. On average, cropland areas in the Cerrado biome had higher utilization (84%) than croplands in the Amazon region of northern Mato Grosso (74%). Areas of more recent expansion had lower utilization than croplands established before 2002, providing empirical evidence for lower suitability or alternative management strategies (e.g., pasture–soya rotations) for lands undergoing more recent land use transitions. This unplanted reserve constitutes a large area of potentially available cropland (PAC) without further expansion, within the management limits imposed for pest management and fallow cycles. Using two key constraints on future cropland expansion, slope and restrictions on further deforestation of Amazon or Cerrado vegetation, we found little available flat land for further legal expansion of crop production in Mato Grosso. Dynamics of cropland expansion from more than a decade of satellite observations indicated narrow ranges of suitability criteria, restricting PAC under current policy conditions, and emphasizing the advantages of field-scale information to assess suitability and utilization.

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1. Introduction

Global production of major commodity crops has risen steadily in recent decades, driven by a combination of intensification (e.g., Foley et al., 2011; Galford et al., 2008; Macedo et al., 2012; Spera et al., 2014; Zeng et al., 2014) and expansion of cropland area (e.g., Meyfroidt et al., 2014; Morton et al., 2006; Ramankutty and Foley, 1999). Recent expansion of commodity crop production has been concentrated in the global south, tilting the balance of the agro-

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economic playing field towards regions of soya and corn production in South America (Aide et al., 2013; Gasparri et al., 2015; Lambin et al., 2013). Increasing yields and expansion of croplands in the Cerrado and Amazon biomes contributed to Brazil's rise to prominence as a global leader in soya production.

Whether the trend of expanding crop production continues in Brazil depends on the amount of potentially available cropland (PAC, following Lambin et al., 2013). Suitability and PAC are related concepts; in this study, suitability for rainfed crop production reflects edaphic, climatic, and crop-specific characteristics, including access to markets. Estimates of PAC are typically a subset of all suitable lands that can be converted for rainfed agricultural based on a set of tradeoffs associated with expansion of agricultural production (Lambin et al., 2013). Tradeoffs for PAC may reflect decisions regarding conservation, greenhouse gas emissions, labor, or governance. Lambin et al. (2013) provided a series of examples where limits on PAC varied according to crop types and local circumstances across major regions of cropland expansion. Recent expansion of crop production in Brazil reflects underlying gradients of suitability and PAC based on the contemporary policy and economic context. Importantly, suitability and PAC vary in both space and time based on crop technology, market demands, and changing policies or governance (Fader et al., 2013; Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013). We may expect, therefore, that estimates of both suitability and PAC diminish in relevance over time. However, few studies have considered the long-term accuracy or effective lifetime of cropland suitability assessments.

Market forces, environmental legislation, and enforcement efforts have changed the landscape of PAC in Brazil over the past decade. As market demand for Brazilian soybeans grew in Europe (Garrett et al., 2013; Nepstad et al., 2006) and China (Godar et al., 2015; Lambin and Meyfroidt, 2011; Lathuillière et al., 2014), it spurred increased production in Brazil, often accompanied by clearing of native Cerrado savannas and Amazon forests (Nepstad et al., 2014). The direct contribution from soya expansion to Amazon deforestation (Morton et al., 2006) led to the Soya Moratorium (SM), an industry initiative that has successfully reduced soya expansion from new Amazon deforestation since 2006 (Gibbs et al., 2015; Macedo et al., 2012; Nepstad et al., 2014). Recent changes in Brazil's Forest Code (FC) have also clarified the requirements for legal reserve areas on private properties (Brazil, 2012; Soares-Filho et al., 2014), further incentivizing cropland expansion on existing cleared areas (Gibbs et al., 2015; Macedo et al., 2012) and spurring the development of new agricultural frontiers in regions with a surplus of native vegetation relative to FC requirements for set-aside areas on private properties (Gibbs et al., 2015; Soares-Filho et al., 2014). The impact of these policy constraints on further cropland expansion in the Brazilian Amazon and Cerrado fundamentally depends on adequate enforcement of environmental laws (Gibbs et al., 2015) and whether suitable lands are abundant or scarce (Lambin et al., 2013).

The extent of suitable cropland has been debated for decades, beginning with the introduction of new management practices during the 'green revolution' (i.e., mechanization and fertilization) and concerns over population growth (e.g., Godfray et al., 2010; Lambin and Meyfroidt, 2011), and, more recently, attention to losses of ecosystem services and other tradeoffs associated with land use transitions (e.g., Foley et al., 2011; Green et al., 2005; Lambin et al., 2013; Rudel et al., 2009). Previous studies of crop suitability have analyzed constraints for crop production at regional (e.g., Jasinski et al., 2005; Soares-Filho et al., 2006; Vera-Diaz et al., 2008) and global scales (e.g., Hurtt et al., 2011; IIASA/FAO, 2011; Ramankutty and Foley, 1999). However, crop suitability changes dynamically in response to factors at the global, regional, and local scales. Regional variables such as governance, market demand, or climate often operate at large scales; they are necessary but not sufficient to support crop production. Local variables such as slope, soil type, or current land cover directly influence the viability of a given land area for crop production. Previous studies of cropland suitability in Brazil have often combined regional and local variables in their assessment (e.g., Jasinski et al., 2005; Vera-Diaz et al., 2008), blurring the spatial and temporal scales over which the suitability assessment is most appropriate.

Here, we compared previously published estimates of cropland suitability to satellite-based maps of cropland expansion over the past decade in the Brazilian state of Mato Grosso. Our analysis provided an empirical test of existing cropland suitability estimates based on the actual dynamics of recent cropland expansion. Annual time series of mechanized crop production derived from satellite data also yielded information on the long-term utilization of croplands, defined as the fraction of years in which crops were planted following conversion to cropland. Spatial and temporal variability in cropland utilization across the Cerrado and Amazon regions of Mato Grosso offered an alternate means to evaluate gradients of cropland suitability and the amount of PAC accessible through intensification. Finally, we estimated the remaining supply of PAC based on the observed cropland dynamics and current land use policies. Empirical data on cropland expansion under current climate and policy conditions supports a critical evaluation of suitability assessment efforts, including evidence for a more limited set of suitability criteria, sharp boundaries in suitability gradients that emerge from remote sensing data at the field scale, and short time scales over which suitability may be reasonably inferred.

2. Materials and methods

2.1. Study region

Rapid cropland expansion during the satellite era and a diversity of physical conditions make the Brazilian state of Mato Grosso an ideal case study to evaluate the accuracy and longevity of cropland suitability estimates. The state is large (>900,000 km^2), with extensive crop production divided between the Amazon biome in the north and the Cerrado biome in the south and east. Cropland expansion since 2000 has been tracked using time series of moderate resolution satellite data (e.g., Morton et al., 2006; Rudorff et al., 2011), given the large size of soya farms in the state database of private properties (mean = 1915 ha; Gibbs et al., 2015).

2.2. Policy context

Mato Grosso is the largest soya-producing state in Brazil, often as part of a double cropping rotation with corn (Galford et al., 2010; Spera et al., 2014), with only 6% of cropland area dedicated to large-scale cotton and sugarcane production in 2013 (IBGE, 2013). Soya has also been a major driver of recent cropland expansion in the state (Gibbs et al., 2015; Macedo et al., 2012; Morton et al., 2006). These factors have given rise to specific policies for soya production in the region, including the SM to limit further expansion through Amazon deforestation (Gibbs et al., 2015; Macedo et al., 2012; Nepstad et al., 2014). The SM is an industry initiative to avoid purchasing soya from areas of recent Amazon deforestation (Macedo et al., 2012; Nepstad et al., 2014; Rudorff et al., 2011), and the SM was recently extended through May 2016 (Gibbs et al., 2015).

Brazil's FC governs conservation of native vegetation on all private properties (not just soya production), stipulating that 80% of each property in the Amazon and 20–35% in the Cerrado be set aside as a "legal reserve" (Brazil, 2012; Soares-Filho et al., 2014).