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"Brasilience:" Assessing Resilience in Land Reform Settlements in the Brazilian Cerrado

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Abstract This study assessed the socioecological resilience of family farms in three land reform settlements in Mato Grosso, Brazil, located in the ecologically threatened Cerrado biome. Using focus groups, a household survey, and analysis of soil samples we characterized farming systems and quantified indicators of resilience, which we contextualized with a qualitative analysis of distributions of power and access to rights and resources. In Mato Grosso, where diversified agriculture is a marginal presence in an industrialized agricultural landscape, none of the communities were achieving participant-defined threshold levels of any measured indicator of resilience. However, farmers who were members of a marketing cooperative selling produce through a federal public procurement program had significantly greater agrobiodiversity, plant-available soil phosphorus, household food self-sufficiency, and access to stable markets. Our pilot study suggests that the convergence of grassroots mobilization and political-institutional change is a central leverage point for developing more resilient food systems.

Keywords Agroecology · Food sovereignty · Brazil · Resilience

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Introduction

Agriculture and food security have a highly uncertain context in the Anthropocene, an epoch marked by unprecedented global change (Crutzen 2006). The awareness that agriculture both affects and is affected by global change has, in turn, sparked concern regarding food system transformation toward resilience. Conversations about how to develop more sustainable and resilient food systems are contentious: dominant policies continue to advance industrial production despite growing calls for scaling up agroecological and family agriculture (Tomich *et al*. 2011; Kremen and Miles 2012; Rosset and Martínez-Torres 2012). Assessing the resilience of a range of food system models is necessary to identify and understand their socioecological outcomes, and to specify mechanisms for developing more resilient and equitable food systems.

Food System Resilience

Ecologists have defined resilience as the ability of an ecosystem to experience disturbance and maintain its basic structure and functions (Gunderson and Holling 2002). They have asked questions such as: resilience of what to what? And, how do we manage for resilience (Carpenter *et al*. 2001)? Robust assessments of *agroecosystem* resilience, specifically, draw on theories from agroecology, which is the application of ecological science to agriculture (Gliessman 2007; Tomich *et al*. 2011).

Ecological knowledge has been applied to design more resilient cropping systems that rely on biotic processes and interactions to sustain production, while reducing external inputs (Shennan 2008). Example management practices that build resilience to disturbance include enhancing field- and farm-scale biodiversity through complex crop rotations, cover cropping, intercropping, and agroforestry, which also increase belowground diversity and soil food web complexity. Ecological approaches to managing soil fertility while reducing external inputs include re-integrating crops and livestock, adding organic nutrient sources such as animal and green manures (especially legumes, which fix atmospheric nitrogen into plant-available nitrogen forms), and building up soil organic matter to enhance the soil's capacity to supply plant nutrients over the long term via decomposition (Drinkwater and Snapp 2007; Jackson *et al*. 2007).

Building food system resilience, however, requires more than just ecological or techno-scientific knowledge (López-Ridaura *et al*. 2002). Food systems are hybrids of nature and society (i.e., socioecological systems; Ostrom 2009). Agroecosystems are embedded in sociopolitical and economic contexts, where the most immediate barriers to resilience include inequity and lack of access to resources. Public and private sector investments, international and national agricultural policies, and failure to regulate agriculture's environmental costs have tended to principally benefit an elite minority and constrain agricultural diversification (Goodman *et al*. 1987; McMichael 2009). The relative resilience of different agricultural models is therefore closely linked to state support. Understanding the sociopolitical relations that are part of food systems, and locating power, agency, and leverage points for change in those relations (Rocheleau 2008), is essential for realizing more resilient food systems.

Resilience Indicators

There is increasing interest in measuring and assessing resilience, which is clearly a multidimensional concept (Carpenter *et al*. 2001). A rapidly growing literature predicts that food systems based on agroecological practices enhance socioecological resilience through a number of mechanisms (Matson *et al*. 1997; Shennan 2008; Kremen and Miles 2012). First, by applying ecological principles to manage diversified cropping systems, it should be possible to maintain production and simultaneously enhance other ecosystem services such as pollination, nutrient cycling, and climate regulation, while also reducing fossil fuel-based inputs and associated harmful emissions from farm fields and upstream input processing. Second, more diverse cropping systems should help buffer farms against environmental and economic shocks if some crops or varieties are less susceptible to particular stresses than others (Jackson *et al.* 2007).

Interest is also growing in linking ecological research methods with sociopolitical analysis of food systems (Perfecto *et al*. 2009; Blesh and Wolf 2014). A number of farming system assessments have combined ecological, sociopolitical, and economic dimensions of sustainability or resilience, often using participatory approaches to develop indicator frameworks (e.g., López-Ridaura *et al*. 2002; Astier *et al.* 2012). Many indicator studies use spider diagrams to display tradeoffs and synergies among multiple outcomes of farming systems. Farmers and researchers can then apply these assessment tools to adapt their management systems to optimize various dimensions.

Farming system indicator studies have advanced the integrated assessment of ecological and socioeconomic variables for specific case studies (Astier *et al*. 2012). However, these frameworks typically focus on household and community level processes, while tending to neglect the role of power dynamics and political economic context, particularly at levels of organization such as institutions and national and international policies. Further, reflexivity regarding identification of performance measures is critical, since the selection process itself involves power, history, politics, ethics, and culture. There are also feedbacks between measures of performance, policy decisions, development trajectories, and the socioecological systems affected by those decisions (Ostrom 2009; Anderies *et al.* 2013). Our study therefore responds to calls for a rights-based resilience framework (Walsh-Dilley *et al*. 2013) relevant to local struggles and policies at multiple scales.

Research Objectives

One promising avenue for advancing an interdisciplinary framework is to link political ecology more strongly with ecological research to analyze the role of power and politics in shaping ecosystem resilience at multiple scales (Peterson 2000; Galt 2013; Turner 2015). In this study, we pilot-tested an interdisciplinary approach to assessing the resilience of small-scale farming communities in three land reform settlements in central-western Brazil that face multiple social, ecological, and economic risks. Specifically, we: i) developed indicators of socioecological resilience jointly with farming communities; ii) analyzed data and samples collected from working agroecosystems to assess their socioecological performance; and iii) interpreted the indicators within a context of distributions of resources and power, especially the right to both the means to produce and consume food.

The Brazilian Cerrado

In Brazil, contemporary social movements have revived land reform and sustainable agriculture as key political issues (Simmons *et al*. 2010; Wolford 2010). Brazil's agricultural frontier in the Cerrado region sits at the center of these debates. The Cerrado is the largest savanna in South America and a biodiversity hot spot (Myers *et al*. 2000), which has become a site of rapid agricultural industrialization supported by national policies and incentives for soybean, sugar cane, cotton and cattle production (Rada 2013). By 2010, Brazil was the second largest producer of soybean globally (FAOSTAT 2014), with the Cerrado accounting for 60 % of national soybean production in the late 2000s (Smaling *et al*. 2008).

Mato Grosso is a large state (~900,000 km^2) in central-western Brazil in the heart of the agricultural frontier. While Mato Grosso had little mechanized crop production before the year 2000, today it is Brazil's leading soybean producer (Macedo *et al*. 2012). In 2011, Mato Grosso had 6,454, 330 ha in soybean production, dwarfing the area of other common commodity crops such as cotton and corn (Fig. 1). Strong public and private sector investment in export commodities (VanWey *et al*. 2013; Rada 2013) has led to a regional sociotechnical infrastructure that offers little support for the diversified family farming sector in Mato Grosso, which is characterized by 90, 000 family farms (80 % of all farm establishments) on over 6.3 million hectares—about the same area as soybean production (IBGE 2009).

While characterization of the soybean complex has highlighted the returns to foreign investment (Wolford 2008; Sauer and Pereira Leite 2012) and threats to ecosystem resilience (e.g., Lapola *et al*. 2014), very little research has characterized and assessed the resilience of other forms of agriculture in the Cerrado. One body of work has explored indigenous farming systems in Mato Grosso, mostly in the Amazon biome (e.g., Vivan *et al*. 2009), as part of a larger literature seeking to understand social and ecological impacts of smallholder farming and government frontier settlement programs in the Amazon (Browder *et al*. 2004; Pacheco 2009). The few studies of family farming communities in Mato Grosso's Cerrado have tended to emphasize socioeconomic and political dynamics (Jepson 2006; Wittman 2009, 2010). A detailed agroecological understanding of diversified farming systems in this region, and their empirical outcomes for resilience, remains a large knowledge gap. We aimed to address this gap through a case study of family farms in Mato Grosso, focusing on land reform communities organized by a Brazilian farmer social movement: *O Movimento dos Trabalhadores Rurais Sem Terra* (the MST, or Landless Rural Workers Movement).

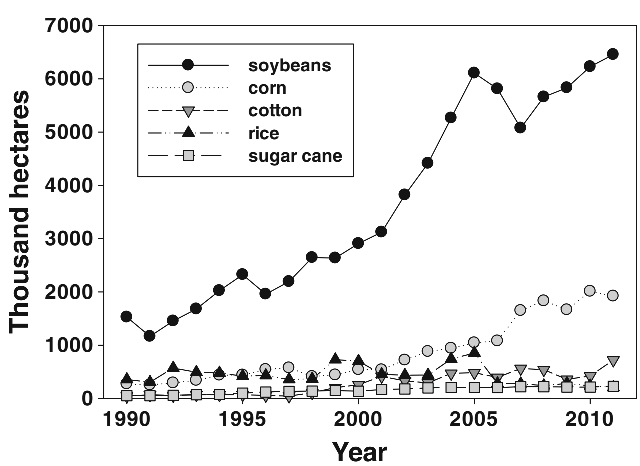

Fig. 1 Area in production of the major commodity crops in Mato Grosso between 1990 and 2011 (in hectares), showing the increasing dominance of soybean production (data from IGBE, 2013)

The MST formed in Southern Brazil in the mid 1980's, and is one of the most significant grassroots agrarian movements in the world. The movement aims to improve social equity and environmental sustainability by occupying land that is legally defined as unproductive and then negotiating with the government to expropriate and distribute the property among the landless poor (Wolford 2010). By pressuring the government to fulfill its constitutional commitment to land reform, the MST seeks to increase access to resources for some of the most vulnerable members of Brazilian society. The national MST leadership prioritizes settlement designs that include forest reserves (Wittman 2010) and trains new farmers to implement diversified, low-input, and organic agricultural systems including horticulture, grains, agroforestry, and rotational grazing. They encourage production of food crops for diverse markets, and have informed the development of public policies for regional and local markets that increase access to food produced using agroecological methods.

The MST is also one of the largest member organizations of *La Vía Campesina*—a transnational agrarian social movement that developed the concept of food sovereignty. Food sovereignty advocates call for the rights of farmers, fishers, and consumer-citizens to determine food and agricultural policy and practice, while respecting cultural and productive diversity (Wittman 2011). Food sovereignty is a farmer-developed concept that foregrounds questions about what food is produced and consumed, how, at what scale, by whom, who benefits, and who decides. The food sovereignty movement promotes the use of agroecological production practices as a foundational principle, and is actively involved in international research and training in agroecology (Rosset and Martínez-Torres 2012).

In 1994, the MST began to work in Mato Grosso, which has the second highest land concentration in Brazil (IBGE 2009). Since 1979, 539 land reform projects have been organized in Mato Grosso by diverse actors including the government, former slave communities, rural unions, and religious organizations, and which span approximately 6 million ha with over 83,000 families settled (INCRA 2012). Of these settlements, 42 were organized by the MST, representing 4250 families settled on 140,500 ha of land.

Our study focused on MST-organized land reform settlements because of the organization's expressed commitments to social equity and environmental conservation. Having been organized around principles of agroecology and food sovereignty, MST settlements are potentially promising sites for food system innovation and resilience. In this study, we assessed implementation and outcomes related to these alternative management practices using an interdisciplinary indicator framework. We addressed several critical questions in a tropical agricultural frontier that has become increasingly brittle following extensive environmental degradation: How can we measure the socioecological resilience of communities advancing agroecology in places where it is especially difficult to achieve? What is the relative importance of different indicators of resilience? How might these small experiments in innovation inform a scaling up of food system resilience?

Methods

Study Area

Mato Grosso spans tropical rainforest in the north (Amazon), savanna/grassland in the center (Cerrado), and wetlands (Pantanal) in the south (Fig. 2a). The Cerrado has a semi-humid tropical climate with distinct wet and dry seasons where the dry season can be longer than 4 months. A recent analysis suggests that regional deforestation is leading to changes in precipitation patterns and water cycles resulting in a longer dry season (Davidson *et al.* 2012). In our study region within the Cerrado, mean annual temperature was 27.3 °C and mean annual precipitation was 1212.5 mm (1999–2011; INMET 2012; Lathuillière *et al.* 2012). The region's soils are predominately Oxisols and Ultisols, which are highly weathered, moderately acidic soils with low activity clays and iron and aluminum oxides, meaning they have a lower capacity to hold nutrient cations such as calcium, magnesium, or potassium compared to less-weathered soils in higher latitudes. Oxisols and Ultisols are also highly phosphorus (P)-sorbing, and crops are prone to P deficiencies (e.g., Cleveland *et al.* 2002).

Site Selection and Sampling Approach

We conducted 13 months of fieldwork between 2012 and 2013 in three land reform communities located in the Cerrado (Fig. 2b). The first site, Antonio Conselheiro (AC), was established in 1998 and is one of the earliest MST-organized settlements in Mato Grosso. It spans 38,335 ha in three different municipalities (Tangará da Serra, Barra do Bugres, and Nova Olímpia), with a total of 970 families. Roseli Nunes, established in 2002, spans two municipalities—Mirassol D'Oeste and São José dos Quatro Marcos—and is 10,611 ha with 350 settled families. The third settlement, Florestan Fernandes, located in the municipality of Araputanga, was established in 2001 and has 150 families settled on 4551 ha. In these three settlements, we sampled land reform beneficiaries ($n=55$) who self-identified as undertaking alternative agroecosystem management related to their commitment to agroecology, in a region where such practices are rare.

Farmers from Florestan Fernandes and Roseli Nunes were members of a regional marketing cooperative called ARPA (*Associação Regional dos Produtores Agroecológicas*, Regional Association of Agroecological Farmers), which formed in 2003 and constitutes a network of families who seek to achieve agroecological management. Our sample from these two settlements included all members of ARPA in 2012 ($n=28$), grouped as one study site. In the second site, the

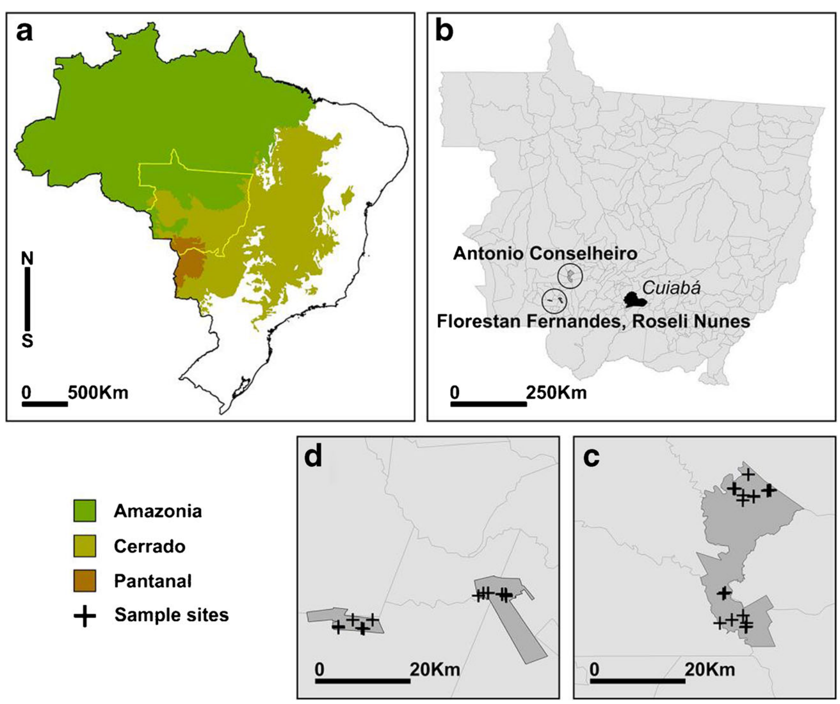

Fig. 2 **a** Map of Brazil showing the Amazon forest, Cerrado and Pantanal ecoregions and the location of Mato Grosso within Brazil; **b** Detail of Mato Grosso showing the location of the capital, Cuiabá and the two study sites Antônio Conselheiro (AC) and Florestan Fernandes/Roseli Nunes (ARPA); **c** Detail of the settlement project, Antônio Conselheiro showing the location of fields where soils were sampled; and **d** Detail of the settlement projects Florestan Fernandes (*left*) and Roseli Nunes (*right*) showing the location of fields where soils were sampled

AC settlement, we sampled 27 families identified as practicing agroecology in an earlier ethnographic study conducted by one of us (Wittman 2010) between 2003 and 2005 and that were still pursuing these practices in follow-up interviews in 2012. Our study sample was therefore not intended to be representative of all families in each of the three settlements. Instead, it was a purposeful, extreme case sample designed to pilot-test the indicator approach with farmers who had over a decade of experience with agroecological production. In the remainder of the article the two study samples are abbreviated as ARPA and AC.

Developing an Indicator Framework

Focus groups

Beginning in January 2012 we conducted 6 focus groups, each with 3–15 participants, including settlement farmers and MST movement leaders. The conversations lasted from 1 to 2 hours. The purpose of the discussions was to generate place-based indicators of resilience relevant to these communities. First, we asked each group what food sovereignty and resilience meant to them. Then, we asked for feedback about how we could measure progress towards achieving these goals in multiple dimensions (e.g., social, economic, environmental) and at multiple levels of organization (e.g., household, community, state, national). Reflecting upon these discussions, we used a hybrid inductive-deductive approach to generate a set of key indicators that we measured with our survey questionnaire and soil samples. Some of the indicators drew upon farmers' perceptions of resilience while others built upon existing definitions of resilience in the literature.

Through this process we defined eight socioecological resilience indicators for farming systems. Farmer-identified indicators included income stability, household food self-sufficiency, milk production, and access to government resources such as technical assistance and markets. Stable household income was measured by asking about each household's "ideal" income and whether or not they were achieving that income through agriculture. We measured household food self-sufficiency as the proportion of household food consumption that came from the farm (ranked as none, some, most, or all) for the 12 most commonly consumed foods (beans, rice, corn, cassava, milk, beef, chicken, pork, eggs, pasta, vegetables, and fruits). Most farmers were raising dairy cows as their primary agricultural income strategy and selected an indicator of milk production (liters/ha of pasture/year) as a measure of resilience. Some dimensions of socioecological resilience are not easily measured or counted. We agreed upon access to stable markets and access to technical assistance as relatively easy-to-measure indices that reflect larger-scale power dynamics and sociopolitical arrangements. We quantified the former with a score based on the type of primary market (e.g., intermediary/ distributor, farmers market, government procurement program – with higher rankings for more stable markets) and whether farmers were marketing crops individually or cooperatively. Rankings for technical assistance were either: none; some in the past; or access to regular and current assistance. Farmers also highlighted the importance of agroecological production for resilient farming systems. We therefore drew upon the ecology literature to identify key indicators of agroecosystem resilience. Soil P was selected as a key indicator of soil fertility, since P tends to limit crop productivity in tropical soils. Agrobiodiversity was measured as the number of crops sold per year; this excluded many species present in kitchen gardens, a metric beyond the scope of this study. We developed an indicator of ecologically-based management of cropping systems, which combined information about use of regular crop rotations, fertility inputs, and legume nitrogen sources. We then interpreted the relatively concise evaluation framework within a historical and political context, and within the context of our field observations on rights-based issues like access to land, and autonomy and equity in decision-making.

Development of the indicator framework was a subjective exercise intended to provide information about progress along multiple dimensions as defined in partnership with communities. Indeed, participant renditions of resilience added to common academic definitions; for example, for these communities resilience means much more than persistence. Though the farm families in our study struggle to continue as a social class within a rapidly changing context, they articulated the desire to live "a *dignified* rural life." We therefore defined threshold, or baseline levels for each resilience indicator that would not just allow families to persist in the country, but to thrive (Walsh-Dilley *et al*. 2013). In this sense, our work extends the use of threshold beyond typical definitions in the ecology literature (i.e., the point where variables defining the state of a system begin to change toward an alternative regime – which, in this case, would likely mean farmers leaving the land reform settlement for work in nearby towns and cities), by incorporating a political ecology perspective that emphasizes access to resources, rights, and equity. The thresholds were therefore determined in one of the following ways: i) agreeing upon an average "baseline" level for a dignified rural life during the focus group conversations; ii) if the indicator was calculated as a nominal variable, the threshold was the highest possible score; iii) for biophysical data (e.g., soil P), threshold levels were determined from regional agronomic extension publications, or from the 75 % quartile of the distribution of survey results (e.g., for agrobiodiversity).

Household Surveys

We operationalized the indicator framework through a survey conducted with the 55 households throughout 13 months of fieldwork in the two sites, ARPA (n=28) and AC (n=27). The survey had five sections: 1) household demographic, social, and economic data; 2) farm-scale land use questions, including sources of management knowledge and previous farming experience; 3) detailed crop rotation information (for at least 5 years, where possible) for fields planted to annuals and perennials, and all corresponding inputs (fertilizers, other chemicals, tillage, irrigation) and quantities of crops sold; 4) production of animal products; and, 5) household food consumption including types, quantities, and source of the most common foods. We combined management and land use information from the survey with analysis of soil samples to assess how soil parameters indicative of ecological resilience varied under different management systems.

Agroecological Assessment

Soil Sampling and Analysis

Managing soil fertility is critical for sustaining production with few to no external inputs (Drinkwater *et al.* 2008). We collected soil samples from 46 fields on a subset of farms (32 farms total), which were purposefully selected to span the full range of management systems and soil types represented in the survey dataset (e.g., grain, pasture, and horticultural fields with differing fertility management regimes, and soils with different textural properties). Samples were collected during the last 2 weeks of March 2012, near the end of the rainy season, when most horticultural crops are planted. Ten to fifteen soil cores (2 cm diameter by 20 cm depth) were composited per field. Fresh soil was processed immediately to determine soil moisture. Samples for chemical analyses were passed through a 2 mm sieve and air-dried. These samples were analyzed at a local agricultural analytical laboratory, *Laboratório Plante Certo*, (Várzea Grande, Mato Grosso, Brazil) to characterize soil texture parameters (% sand, silt and clay), pH, plant-available P (Mehlich I) and other macronutrients, and cation exchange capacity. We used Kopeck rings (5 cm diameter×5.3 cm length) to measure bulk density in the field. The bulk density samples were removed from the Kopeck rings, dried at 105 °C, weighed and discarded.

Particulate Organic Matter (POM) Pools and Soil C and N

We measured other soil characteristics on a subset of fields, in order to provide additional information about agroecosystem management and soil quality in these sites. These metrics build on research in temperate grain systems demonstrating the potential for more diverse crop rotations, and legume-based nutrient management, to balance nutrient budgets and enhance soil nitrogen (N) cycling capacity (Schipanski and Drinkwater 2010; Blesh and Drinkwater 2013), and also build on similar findings in tropical agroecosystems (Snapp *et al.* 1998). Soil organic matter is comprised of heterogeneous fractions that turn over on timescales ranging from hours to centuries to millennia. Particulate organic matter (POM) fractions are responsive to short-term management changes and serve as an indicator of soil quality and the capacity for mineralization to supply nutrients to crops on timescales relevant to farmers (Wander 2004).

Air-dried soil from a subset of soil samples (n=38), representing the full range of management approaches, was analyzed for POM pool size and carbon (C) and N content. We separated light fraction POM (also called free POM, or fPOM) and occluded POM (oPOM) on 40 g subsamples of soil using a size and density fractionation method (Marriott and Wander 2006). The fPOM fraction (250 to 500 μm, and macro organic matter) is derived from recent root and litter inputs. The oPOM fraction (53 to 250 μm), in contrast, is physically protected within soil aggregates, and is typically more decomposed than fPOM (Marriott and Wander 2006). Total C and N of the fPOM and oPOM, and of total soil (to 20 cm), were measured on a Leco 2000 CN Analyzer (Leco Corporation, St. Joseph, MI).

Statistical Analysis

Statistical analyses of survey and soil sample data were computed using JMP v.10 software (SAS Institute Inc., Cary, NC). All variables were tested for normality. Soil P was log-transformed to fit a normal distribution. We used Student's t-tests to calculate pairwise comparisons across sites (AC and ARPA). Site differences for categorical variables were analyzed using Chi-Squared tests.

Since the soil variables we measured are highly correlated (i.e., multicollinear), we also used Principal Components Analysis (PCA) to eliminate redundancy in the univariate analyses and to identify major sources of variability in the data (i.e., environment vs. management). PCA was performed on the following soil variables: percentage sand, percentage clay, pH, total N, P, potassium (K), and calcium (Ca), combining all soil data from the AC and ARPA sites. Principal components with eigenvalues greater than 1 were retained.

Results

Resilience Indicators

The indicators of socioecological resilience calculated using data from the farmer survey and analysis of soil samples are shown in Fig. 3 and mean values (or scores) and standard errors for each indicator are presented in Table 1. The total area of the spider diagram (Fig. 3) represents progress toward farmer-defined characteristics of more resilient farming systems in each study site. Our analysis revealed that the farm

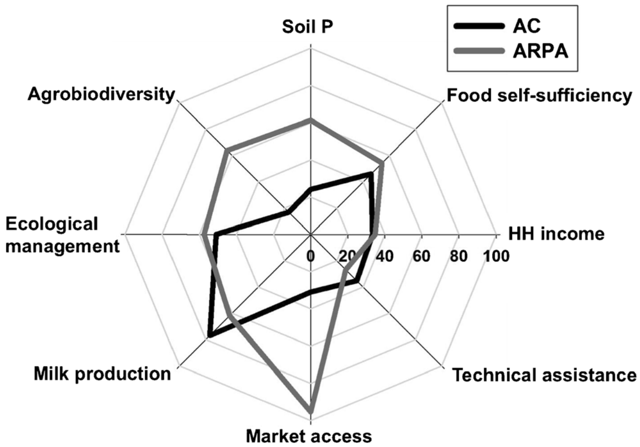

Fig. 3 Webgraph comparing the socioecological indicators of resilience for farmers in the ARPA and AC sites

households we surveyed are not at the threshold level for any indicator. However, the total area of the spider diagram was greater for farmers in ARPA, due to significantly greater agrobiodiversity, plant-available soil P, access to stable markets, and household food self-sufficiency. There were no significant differences across sites in the household income, ecologically-based management, milk production, or technical assistance indicators (Table 1).

The focus group conversations to generate the indicator set, and follow-up interviews with farmers and settlement leaders, revealed complex conceptualizations of resilience, which were linked to food sovereignty and encompassed multiple dimensions of food systems. Regarding production, discussions centered on agroecology. Participants defined agroecology as a new technological model that involves participatory research and knowledge exchange among farmers, and that improves environmental sustainability and resilience, especially by managing farms for agrobiodiversity and preservation of wild biodiversity. They cited the importance of soil conservation, and reducing or avoiding chemical inputs through use of legumes, manure, and natural pest control methods. Participants highlighted the importance of access to resources to plant and harvest crops, including seeds, and control over production. One farmer noted that land reform is central: "For us, land is the means of production. Land reform is not just about getting land, it's also about organizing ourselves around how to produce on the land, and building small industries for a sustainable income."

Household income and rural livelihoods were recurring themes. As one farmer put it: "income is essential." Across the focus groups, the general consensus was that a threshold cash income for a family of 4–5 of two minimum wages (approximately R$1244/month in 2012), would allow for a dignified livelihood, buffering against the risk of migrating to urban areas. Farmer cooperatives were cited as a means to increase economic resilience. One farmer said: "those who aren't organized [in an association] are more susceptible to what comes from outside," referring to price shocks, and selling products through market intermediaries. One farmer noted that the "target income" agreed upon by the group accounted for self-provisioning from the land: "Food sovereignty means not being hungry, having the necessary foods for subsistence, and the necessary land and income to feed your family." Other farmers mentioned the importance of nutritious food for health: "for 5 years now we have grown a large garden, and we eat what we plant there. It's healthier than what we purchase at the store." Another participant noted that exchange of food is important as well; that is, every individual shouldn't have to grow the entire household diet, but by organizing their production the communities' food needs can be more sustainably met.

The understanding that resilience has to do with control over production and consumption led to a broader discussion about adaptability, rights, and resources, including social and biophysical factors at multiple scales that can support or constrain agroecological production. At the farm or household level participants listed gender equity as important, in terms of the role of women on the farm and in farm decision-making. Others raised issues at larger spatial scales saying: "We have to fight for government resources in order to succeed." Participants generated a long list of resources essential for thriving in rural land reform communities, including access to appropriate technology to reduce manual labor, technical assistance, health services, education, transportation and good roads, internet access and communication, and leisure activities. Several of these items were discussed in reference to the important problem of how to keep youth on the farm and thus sustain the farm through generations. Others linked these issues citing the need for "good public policies to support agrarian reform, small-scale production, rural livelihoods, and access to food in cities."

Household Characteristics

Table 2 lists select descriptive statistics (means and standard errors) for the farm households we surveyed (n=55) and their basic land use characteristics. On average, the highest level of education of a household member was approximately 6 years. The mean agricultural labor input was two full-time equivalents. The average farm size in AC was 33.4 ha and for ARPA it was 26.3 ha—within the range of the legally defined Brazilian "family farming sector," but considerably smaller than the average farm size in Mato Grosso (430 ha). In AC, farms were located an average of 58 km from the nearest city, compared to an average distance of 26.2 km for the ARPA sample.

The household food self-sufficiency score was significantly greater for ARPA farmers than for AC farmers (Table 1; P= 0.026). Analysis of the survey scores for individual foods indicated that the difference in the household food self-

Table 1 Participatory indicator framework developed in partnership with farming communities: indicators of socioecological resilience, units, raw scale, and a brief description of how the threshold level for each indicator was determined

Indicator	Units	Raw scale			How threshold was determined	ARPA		AC		*P*-value*
		Min	Max	Threshold		Mean (SE)	%	Mean (SE)	%	
Household income	Proportion of farmers responding they receive an "ideal" income through farming	0	1	1	Farmer survey and focus group questions about ideal income (Reais/month)		34.78		33.33	0.9200
Food self-sufficiency	Survey score based on whether none (0), some (1), most (2), or all (3) household food came from the farm	0	39	39	Selected 100 % of food from farm	21.2 (1.05)	54.36	17.96 (0.93)	46.05	0.0261
Soil P	% of sampled fields that have recommended soil P (Mehlich I mg kg^{-1})	0	100	100	Regional extension recommendations for clayey and sandy soils	61.4 (10.4)	61.40	24.2 (3.85)	24.20	0.0011
Agrobiodiversity	Total number of crops sold/year	0	22	15	Selected 75 % quartile of survey distribution	14.04 (0.60)	63.82	3.7 (0.52)	16.82	<0.0001
Ecologically-based management	Survey score based on regular use of crop rotations, fertility inputs, and legume N sources	0	4	4	Highest possible score from survey questions	2.3 (0.25)	57.50	2.04 (0.26)	51.00	0.4978
Milk production	liters/ha/year	85	3086	1100	Selected 75 % quartile of distribution	680.7 (77.7)	61.88	846.5 (209)	76.95	0.9128
Market access	Survey score based on type/stability of primary market, and whether farmers market crops individually or cooperatively	0	3	3	Highest possible score from survey question	2.86 (0.9)	95.33	0.93 (0.18)	31.00	<0.0001
Technical assistance	Survey score based on access to assistance (frequency and quality)	0	2	2	Highest possible score from survey question	0.54 (0.17)	26.80	0.70 (0.15)	35.20	0.4568

Mean values or survey scores for each indicator are shown, with statistics for pairwise comparisons of means across sites. The % column shows each indicator as a percent of the threshold value and is plotted in Fig. 3

*From Student's *t*-tests comparing ARPA and AC for all indicators, except for household income, which is the *P*-value from a χ^2 test

Table 2 Means and standard errors for selected farm household and land use characteristics based on survey data for the entire sample combined (all farmers surveyed) and separated by site (AC v. ARPA)

	All farmers		AC		ARPA		*P*-value
	Mean	SE	Mean	SE	Mean	SE	
Farmer/household characteristics							
Years of formal schooling	6.2	0.5	5.7	0.8	6.2	0.8	ns
Number of adults working on lot	2.6	0.2	2.4	0.2	2.4	0.2	ns
Distance to nearest city (km)	39.5	3	58	3.2	26.2	3.3	***
Labor: total hours/week/household	77.9	5.2	74.3	7.4	76.6	8.1	ns
Land use characteristics							
Size of lot (ha)	30.5	1.8	33.4	2.4	26.3	1.7	*
Annual crops (ha)	2.9	0.4	3.2	0.53	2.4	0.5	ns
Perennial crops (ha)	1.6	0.4	1.2	0.3	1.3	0.6	ns
Pasture (ha)	13.6	1.2	9.9	1.3	14.8	1.2	**
Native forest or reserve (ha)	7.4	1.3	12.3	2.4	3.6	0.8	***
Secondary forest or brush (ha)	5.2	0.9	7	1.7	4.2	0.9	ns
Certified organic			0 %		75.0 %		***
Dairy (*laticina*)			40.7 %		85.7 %		***
Number of cows	21	2.4	14.3	3.2	26.3	3.7	*
Number of chickens	57.9	16.8	45.4	7.9	36.7	5.6	ns
Number of pigs	5.1	1.8	3.5	1.2	3.1	0.7	ns

Significance of *t*-test (or X^2 test for organic and dairy data) comparing AC vs. ARPA is given in the *P*-value column (*$p<0.05$; **$p<0.01$; ***$p<0.001$; *ns* not significant)

sufficiency indicator was driven by significant differences in consumption of rice, milk, and vegetables produced on farm (all significantly greater for ARPA than for AC; data not shown). Nearly 100 % of families in both sites responded that they get “all” of their cassava from the farm or neighbors, and the majority of families (68 %) responded that they get “most” of their fruits and vegetables from their farms.

Land use Characteristics

The greatest farm-scale land use was pasture for ARPA and forest reserve for AC farmers (Table 2), with small amounts of land in annual and perennial crops (2.9 and 1.6 ha, respectively) in both sites. The significant difference in pasture corresponded with a significant difference in the proportion of surveyed farmers selling milk (85.7 % in ARPA vs. 40.7 % in AC), and with a greater mean number of cows per household in ARPA. In addition, most households across both sites raised chickens and pigs, largely for household consumption, with some families selling limited quantities of eggs or meat.

On average, 37 % of individual farm lots in the AC sample were in native forest reserve compared to 14 % of lots in the ARPA sample. However, the settlements also each contained a communal forest reserve. At AC the communal reserve is 5750 ha. There is 5020 ha total of forest reserve in the Roseli Nunes settlement—including both individual and communal areas—or, about 50 % of the total settlement area. These settlement reserve areas (individual plus communal) exceed the requirements of Brazil’s Forest Code for the Cerrado (Soares-Filho *et al*. 2014).

Seventy-five percent of farms in the ARPA sample were producing organic products certified through the Organization of Social Control (OSC) participatory peer certification program of the Ministry of Agriculture, developed in 2007 to support farmers who cannot afford third-party organic certification. It allows the direct sale of organic products to consumers as long as a farm is a member of the particular OSC, usually through a farmer cooperative. None of the farmers sampled in AC had this certification.

Soil Characterization

In both sites, soils were slightly acidic (pH=5.3, Table 3). There were no significant differences in total C and N content across sites; the mean for all fields was 33.3 Mg C ha^{-1} and 3.9 Mg N ha^{-1}. The ARPA soils had significantly more plant-available soil P (Mehlich I), and a significantly lower C:N (Table 3). There were no differences across sites in soil K, Ca or bulk density. We found wide variability in soil texture parameters. Across all fields sampled, % sand ranged from 10 to 82 %, % silt from 5 to 38 %, and % clay from 12 to 85 %. The soils in the ARPA site were significantly sandier, on average, and the soils at the AC settlement had significantly greater clay content.

For all fields we sampled, there was a significant, positive relationship between % clay and the size of the oPOM pool

Table 3 Means and standard errors (in parentheses) for soil variables measured to 20 cm depth for all fields combined, separated by site, and analysis of site effects (*$p<0.05$; **$p<0.01$; ***$p<0.001$; *ns* not significant)

	All fields	AC	ARPA	Site effects *P*-value
pH	5.3 (0.1)	5.2 (0.2)	5.5 (0.1)	ns
Sand (%)	49.0 (3.1)	36.8 (4.3)	64.4 (3.0)	***
Clay (%)	36.5 (2.7)	43.8 (4.4)	24.9 (2.1)	***
Total N (Mg ha^{-1})	3.9 (0.3)	3.5 (0.3)	4.3 (0.4)	ns
Total C (Mg ha^{-1})	33.3 (1.9)	34.7 (3.0)	31.9 (2.4)	ns
C:N	8.8 (0.3)	9.7 (0.3)	7.9 (0.3)	***
P (kg ha^{-1})[a]	15.4 (2.2)	7.7 (1.4)	25.8 (3.9)	***
K (kg ha^{-1})	389.2 (25)	422.5 (33)	352.7 (37)	ns
Ca (kg ha^{-1})	2278 (264)	2332 (385)	2216 (365)	ns
Bulk density (g cm^{-3})	1.14 (0.03)	1.18 (0.05)	1.16 (0.04)	ns

[a] Log-transformed for statistical analysis

(data not shown, R^2=0.26, P=0.001) and between % clay and the N content of the oPOM pool (Fig. 4a). The POM N content (Fig. 4b) was significantly greater in fields that had nutrient amendments (predominantly the ARPA fields, which received composted chicken manure and some dairy cow manure inputs) compared to fields managed with no fertility inputs (i.e., unfertilized) for both the fPOM (43.6 v. 32.2 kg N ha^{-1}; P= 0.013) and oPOM pools (57.3 v. 38.8 kg N ha^{-1}; P=0.001). The analysis for oPOM included % clay as a covariate because of the significant relationship between clay content and the oPOM N pool.

Cropping Systems Management

The farmer surveys indicated a range of grain and horticultural management systems coexisting side-by-side within settlements, or even on the same farm. The two dominant systems were: i) crops grown at larger spatial scales of 1–2 ha on average, such as perennials like banana, cassava, papaya, and sugar cane; or annuals such as corn, which farmers were managing with little to no nutrient inputs, and ii) smaller scale (average 2000 m^2) horticultural areas for producing diversified vegetable crops, typically receiving manure inputs with some use of leguminous cover crops. Both categories were present in both study sites, however the small-scale horticultural areas were primarily found at the ARPA site.

Of the farmers we interviewed, 15 % used no fertility inputs (for any of their crops). A significantly greater proportion of farmers in ARPA used manure amendments compared to farmers in AC (92.8 and 48.1 %, respectively; χ^2=14.5, P= 0.0001), whereas in AC a significantly greater proportion of farmers used chemical fertilizer compared to farmers in ARPA (22.2 and 8.3 %, respectively; χ^2=4.7, P=0.03). There was no significant difference in legume use across the two sites; on average, 42 % of farmers surveyed had used a leguminous green manure in their crop rotation within the past 5 years. The three fertility sources: fertilizer, animal manure, or legumes, can be applied in various combinations, thus the proportions do not add up to 100 %. On average, 88 % of the farmers we surveyed use a tractor on their farms, and 31 % irrigate their horticultural crops, mostly by hand or using drip irrigation systems.

We found that ARPA farms had significantly greater agrobiodiversity than AC (i.e., mean number of crops sold: 14 v. 3.7, respectively, P<0.0001; Fig. 5a) and significantly greater plant-available soil P (Fig. 5b; P<0.0001) compared to farms in AC. In AC, Mehlich I soil P ranged from 1.5 to 28.6 kg P ha^{-1} across the fields sampled, and in APRA the

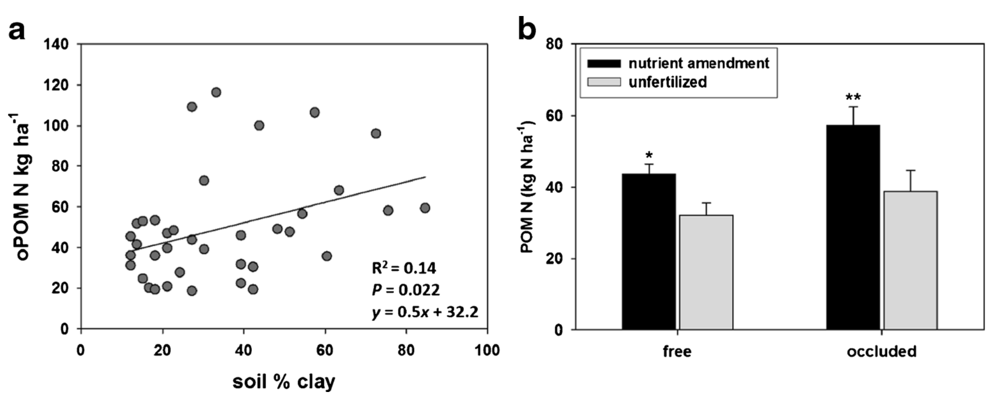

Fig. 4 **a** Relationship between the soil texture parameter, % clay, and the amount of N in the occluded POM pool. **b** The N content of free (fPOM) and occluded (oPOM) pools for fields that had fertility inputs (fertilizer, manure, or legumes) and fields that had no fertility inputs

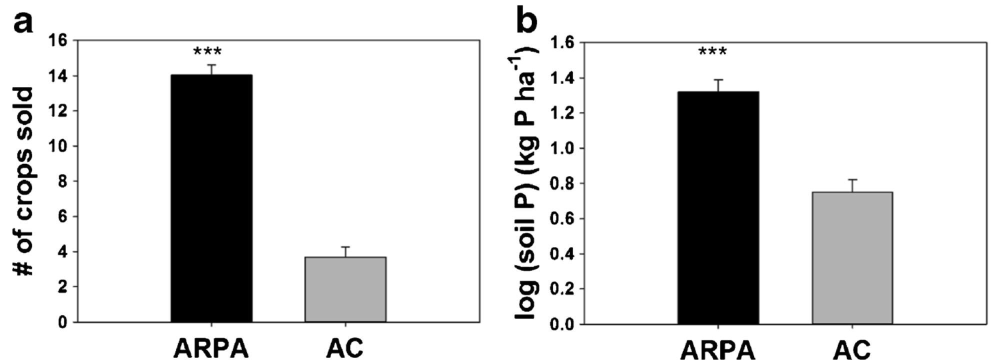

Fig. 5 **a** Agrobiodiversity (# of crops sold) for farmers in ARPA and AC; **b** Extractable soil phosphorous (Mehlich I) for fields in ARPA and AC; *** $p<0.0001$

range was 5.1–66.4 kg P ha^{-1}. The smaller scale vegetable plots in the ARPA site were more intensively managed and received greater inputs of animal manure and compost.

Market Arrangements

In the early 2000s, Brazil launched a Zero Hunger (*Fome Zero*) policy that encompasses many different programs supporting the family farming sector, including the Food Acquisition Program, or PAA (*Programa de Aquisição de Alimentos*). The PAA commits federal and local governments to purchasing products from family farmers, at fair prices, to increase and diversify production by providing stable market access and lines of credit. There is a 30 % price premium for organic products sold through PAA, which contracted farmers receive directly. In addition, the PAA focuses on procuring products from targeted categories of family farmers including organic and women farmers, members of cooperatives, and land reform settlers. Various organizations and social movements, including the MST, were involved in developing the PAA program.

Across all farmers surveyed in the AC site, 16.3 % of produce was sold through the government's PAA program, and the greatest proportion of their crops (35 %) was sold to intermediaries. Their other markets included the farmers market (25 %) and nearby supermarkets (5.4 %). Remaining items were typically sold to neighbors (18 %). In sharp contrast, over the past 5 years, farmers in the ARPA site have begun to rely on the PAA program as their primary market (87.9 % of products, and all farmers surveyed were participating). The group's cooperative marketing structure, the relatively stable market provided by PAA, and the price premium for organic products have driven this marketing shift. In interviews, ARPA members credited the PAA with creating incentives for a shift in cropping systems towards diversified and organic production, including access to stable markets and a price premium for organic produce. Other markets at the ARPA site were the farmers market (3.6 % of products sold), the supermarket (5 % of crops), intermediaries (2.1 %) and neighbors (1.4 %).

Environmental vs. Management-induced Site Differences

We used PCA to reduce the dimensionality of the soil variables. In particular, we wanted to understand whether the significant difference in soil P (the indicator of soil fertility in the framework) for ARPA and AC farms was due to the shift in management towards horticultural production, or whether it was associated with differences in environmental characteristics of the two sites. The two sites varied in management regimes – since all of the farmers in the ARPA site were selling products through the PAA program – as well as in background soil characteristics.

Principal components analysis resulted in two principal components that accounted for 64 % of the variation in the soils data (Table 4), and identified two main sources of variability. The first principal component (PC1) was composed of soil properties that likely reflect background environmental characteristics of the sites: % sand and % clay (soil texture) had the strongest, and inverse, loadings, followed by K and pH. Soil P had the strongest loading on PC2, which accounted for 26 % of the variation. There was a clear separation of the two sites (AC and ARPA) along the PC2 axis (Fig. 6). This separation, together with the high loading of soil P on PC2 (rather than clustering with other soil variables on PC1), suggests that the difference in soil P between the two sites is management-imposed. Specifically, the manuring of smaller

Table 4 Principal component eigenvalues, variation explained, and loadings for two principal components that explain a total of 64 % of the variation in the soils dataset

	PC1	PC2
% Variation explained	38	26
Eigenvalue	2.64	1.82
Variable loadings		
Sand	−0.80	0.54
Clay	0.79	−0.50
pH	0.61	0.61
N	0.50	0.15
P	0.05	0.79
K	0.76	0.18
Ca	0.42	0.48

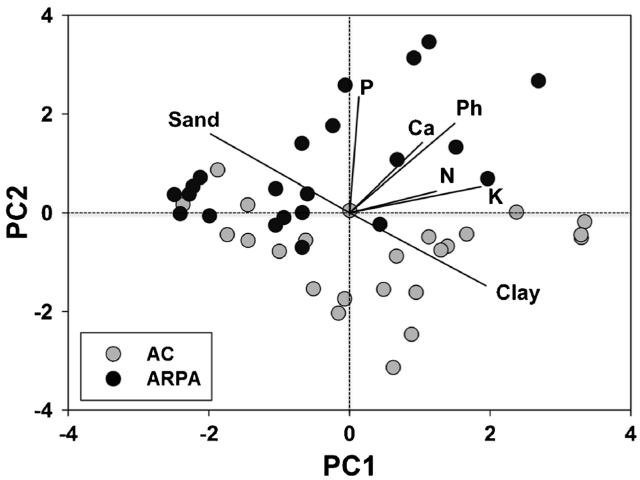

Fig. 6 Bi-plot of principal component (PC) scores for each field by site (AC or ARPA) and variable loadings (correlations between soil variables and PCs) for PC 1 and PC 2, which explained 38 and 26 % of the variability in the dataset, respectively

horticultural plots for production for PAA markets likely led to this difference in P across sites.

Discussion

In Brazil's export agriculture frontier, the resilience of agroecological and diversified family farms is understudied. We used a participatory approach to generate and interpret indicators of agroecosystem and socioeconomic resilience in this region. While our approach extends and departs from purely ecological framings of resilience, it builds on other socioecological indicator assessments of farming systems (e.g., Astier *et al.* 2012), drawing on political ecology to pay greater attention to political economic context, rights, and resources at multiple levels of organization.

Though the national MST leadership promotes agroecology, adoption of agroecological management on farms is highly variable. We purposefully sampled a subset of farmers from two study sites who self-identified as practicing agroecology, though these families made up a small proportion of all families in these settlements. Even within this purposeful sample of agroecological farms, we found a wide range of management practices: from relatively low-diversity rotations with either no fertility inputs or some use of commercial fertilizer and other chemical inputs, to highly diversified, certified organic production for local and regional markets.

The indicator framework (Fig. 3) shows that farm households were not achieving threshold levels of resilience for any of the indicators. Challenges to the success of agroecological practices are related to the interconnected biophysical, economic, and sociopolitical context of production in the Cerrado. In terms of biophysical factors, the region has challenging environmental conditions for agriculture including acidic, low fertility soils with high P-binding capacity, high temperatures and a long dry season that appears to be lengthening (Davidson *et al.* 2012). We also found large variability in soil texture within study sites, which affects not only fertility and moisture status of a given field, but also impacts the applicability of management knowledge shared among farmers.

In addition to challenging biophysical conditions in the Cerrado, the sociopolitical and economic context of what has been called the neoliberal food regime (McMichael 2009) constrains the success of small experiments in agroecology and food sovereignty here. For example, at a national level, in 2013 the Brazilian Ministry of Agriculture budgeted US$62 billion in loans, grants, and capital investment for the agribusiness sector (16 % of all farms), while the Ministry of Agrarian Development allocated $39 billion to the family farm sector (84 % of all farms) for loans, agricultural extension, and public nutrition programs such as the PAA (Graeub *et al.* 2015). The specialization and intensification of agriculture are especially pronounced in the Cerrado, which was targeted as an agricultural frontier for export soybean production. This orientation led to development of a sociotechnical infrastructure that supports commodity farmers who have very different needs from small-scale farmers producing crops for regional consumption, which has increased the vulnerability of the family-farming sector. It has also driven differential access to critical resources for rural livelihoods including technical assistance, knowledge, subsidies, and credit.

We found that the management systems and market channels differed across sites. Farmers in the ARPA site had smaller-scale, more intensively-managed horticultural cropping systems with significantly greater socioecological resilience driven by four of the indicators we measured: soil P, agrobiodiversity, access to stable markets, and household food self-sufficiency. Results from the stakeholder interviews suggest that the shift in management systems was due to ARPA's increasing involvement in the Brazilian PAA program, indicating that access to state resources can drive differences in resilience across communities. In designing this pilot study, we did not anticipate that the government's PAA program would emerge as such an important factor, and did not design our sampling scheme to test the impacts of the PAA. Since all of the farmers we surveyed in ARPA were participating in PAA (vs. just seven of the AC farmers) we were not able to statistically analyze differences in the indicator set based on PAA contracts. However, interviews with farmers and other stakeholders suggest that the PAA has created incentives to diversify production by increasing market access. In the ARPA community, farmers expanded their production to include horticultural products (e.g., leafy greens, carrots, okra, potatoes, squash, beets, tomatoes, herbs, and fruits), while also maintaining previously established production systems (e.g., banana, cassava, corn, and animal production), thereby enhancing overall farm-scale agrobiodiversity. Farmers in PAA have 6-month contracts, which help to determine their cropping plans and guarantee there will be a market for those crops.

On the weathered Cerrado soils, fertility amendments are essential for sustaining crop production; however, if crop prices are low and market connections are poor, there is little incentive to invest in improving soil fertility. The PAA program provides a positive incentive (i.e., the 30 % price premium) for transitions to organic production. We found increased soil P levels on ARPA farms, whose organic production model relies on animal manure, compost, and legume nitrogen fixation as nutrient sources. Though 42 % of our sample had planted leguminous green manures at some point over the past 5 years, only 21 % were using them regularly in crop rotations. Our interview data indicates this was due to a lack of access to seeds, technical assistance, and management knowledge for legume production. Animal manure was the most readily accessed organic input for this set of farmers. For farmers in ARPA there were two main sources of manure: their own dairy cows (which they had more of, on average, than farmers in AC), and a nearby chicken confinement operation in Mirassol D'Oeste that sells composted chicken manure. It is not surprising that a greater number of farmers in the AC site were using chemical fertilizer compared to the ARPA site. A smaller proportion of farmers at the AC site participated in PAA, and therefore did not receive a price premium for organic production. Also, the AC settlement suffers from poor road conditions, and AC farmers were located a significantly greater distance from the nearest town compared to ARPA farmers. Chemical fertilizer is readily available in the municipalities closest to AC, which are centered on industrial production, and fertilizer is easier to transport than animal manure.

In terms of soil fertility status, we selected P as an indicator because production tends to be P-limited. In addition, we also measured soil POM pools and their N content for a subset of fields to gain a broader understanding of soil nutrient cycling on these farms, since POM is known to respond to short-term management changes. Nitrogen is also an essential nutrient frequently limiting to crop production, and N in fPOM and oPOM pools provides additional information about agroecosystem resilience, particularly the capacity of soil microbial processes to supply plant nutrients. These metrics—plant available soil P, and POM pool size and N content—reflected the effects of increased manuring rates on smaller-scale horticultural plots in the ARPA study site. The significantly lower C:N of soils in the ARPA site potentially also reflects the greater nutrient amendments.

Soil texture is an important predictor of soil fertility. Soil texture impacts C-stabilization in SOM, decomposition rates, nutrient status, and drainage properties. Clayey soils have greater cation exchange capacity, and organic matter trapped in clay aggregates can be protected from decomposition. Our results support this understanding—for samples collected from working farms we found a positive correlation between the size of the oPOM fraction (and POM N content) and soil % clay. On average, the ARPA soils were significantly sandier than the AC soils (Table 3). Even though clayey soils are often more fertile than sandy soils, we found that management differences—in particular, animal manure additions—improved soil P status even in sandy soils. Together with the multivariate analysis indicating that the two study sites were segregated along a principal component with the highest loading from soil P, these data support the interpretation that shifts in management have increased soil fertility in the ARPA site.

We did not find a statistically significant difference in the household income indicator across sites, even though farmers in the ARPA site had greater access to stable markets. The score for both sites was well below the farmer-defined threshold level for a dignified rural livelihood. One possible interpretation of the lack of difference between sites could be a time lag, since ARPA has only had success with its members' PAA contracts since 2009. The group experienced many bureaucratic and logistical challenges when they first entered the program, with the consequence of not consistently receiving payment for their products (Wittman and Blesh in press). These difficulties have mostly been resolved, and ARPA's membership is currently increasing. Our interview data suggest that ARPA farmers perceive their income to be more stable than it was before participation in the PAA program.

These differences across communities reflect differences in access to state-level programs for family farmers at smaller scales. For example, in addition to the challenges already mentioned for the AC community (poor roads; farther from surrounding cities), the community is affected by a municipal government that is strongly supportive of soybean farms, and unsupportive of more diverse forms of production, and thus is at a disadvantage in terms of accessing state resources. Due to large inequities in power in Mato Grosso, for the farmers we sampled it was advantageous to be organized into a marketing cooperative, to improve access to markets and government resources. The ARPA community has successfully formed a marketing association to enroll in the PAA program in addition to accessing lines of credit and infrastructure that settlement farmers who market as individual households cannot access. Further, they have benefitted from a more supportive municipal government, which, for example, has provided reliable transportation to get their products to market. The ARPA community also had greater competencies regarding forming an association and practicing agroecology due to several leaders with previous experience in diversified agricultural production and a strong commitment to environmental stewardship. The association also pooled resources to hire a coordinator with administrative experience who handles the difficult logistics of enrolling in PAA.

Brazil is perhaps well-positioned for improved food system resilience at a national scale compared to other countries with rapidly industrializing agricultural sectors (Graeub *et al*. 2015). Beyond just land reform policies, the suite of social welfare policies under Zero Hunger (*Fome Zero*) increase power, access to rights and resources, and equity for marginalized populations. In particular, the PAA public procurement program and the National School Lunch Program (PNAE: *Programa Nacional de Alimentação Escolar*), which requires that 30 % of school lunch menus be sourced from small-scale farmers, have the potential to institutionalize and scale up food sovereignty by supporting agroecological production and by linking the right to produce with the right for communities to access healthy foods. Such programs commit to sustaining local markets via a price premium, stable prices, and a steady demand. Diverse actors promoting such food sovereignty policies, like the MST, seek transformative social change achieved through fundamental changes in food systems governance.

The PAA program has expanded over the past decade with the number of farmer participants nationally increasing from 41,300 to 128,800 (CONAB annual reports, 2003–2012). Public procurement has significant leverage to scale up agroecological practices since public institutions (e.g., schools, hospitals, civil service organizations) are important purchasers of food. To date, however, the PAA has had limited reach in Mato Grosso, where the number of program participants represents just 5 % of the target population in Mato Grosso. Future research should explore relationships between Brazil's Zero Hunger programs and socioecological resilience.

This case study of '*Brasilience*' shows a site-specific improvement in socioecological resilience of smallholder farmers who participate in the government's PAA program through a marketing association (ARPA). Our results are an example of specified resilience (Anderies *et al*. 2013) for agroecological practices in a specific place, which reflects a confluence of factors. First, these farmers were settled in land reform communities due to the organization and mobilizing efforts of one of the most significant grassroots political movements in Brazil. The MST has pressured the government to fulfill its constitutional commitment to land reform, and to provide Brazil's rural poor with secure land tenure and access to resources, including targeted marketing opportunities. The MST also pressures the government to locate settlements close to urban centers. This, together with increasing consumer demand for local and organic foods, represents increased regional marketing opportunities for agroecological production.

Conclusion

We conducted a participatory pilot study in two study sites to evaluate the socioecological resilience of agroecological production in the Brazilian Cerrado. Our assessment linked ecological and political ecological theory. Findings from focus groups, a household survey, and biophysical sampling demonstrated that the interface of a social movement with public policy change (itself driven largely by social movement demands) created incentives for the development of diversified, horticultural cropping systems with reduced chemical inputs and investments in soil fertility, through improved access to stable markets for sales of regional, organic foods. These farming system changes have improved food system resilience at multiple levels: from increasing field and household scale agrobiodiversity, soil nutrient status, and food self-sufficiency to supporting regional food security. In this case study, secure land tenure achieved through land reform was a necessary but insufficient condition for enhanced socioecological resilience. Access to land enables small-scale farmers to opt out of regional crop lock-in when coupled with both a commitment to agroecology and stable and farmer-friendly market channels. In addition to land reform, civic engagement by the MST and regional NGOs with government social welfare programs such as the PAA have the potential to advance socioecological resilience, though more research is needed to specifically test the impacts of the PAA program. There is also a pressing need for research and development on agroecology in the Cerrado to support its success in difficult environmental conditions and to optimize low-input management systems by linking farmer and scientific knowledges. This case study informs leverage points for scaling up socioecological resilience: change is needed at all levels of organization, with an emphasis on access to a supportive sociotechnical infrastructure, fair and stable markets, and agroecological knowledge.

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