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A brighter future: Complementary goals of diversity and multifunctionality to build resilient agricultural landscapes

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A B S T R A C T

Humanity places a heavy burden on agricultural landscapes, demanding plentiful food, multiple ecosystem functions, and biodiversity conservation. We quantified areas growing 'brighter' and 'darker' (i.e., better or worse than expected based on extrinsic constraints) for multifunctionality of ecosystem services (ES) over time across a dynamic agricultural landscape. To explore how areas changing in ES multifunctionality, we likewise explored temporal changes in additional features of resilience in social-ecological systems, including: (1) species functional richness and dispersion, (2) agrobiodiversity, (3) the diversity of farm characteristics and human demographics in the area, and (4) landscape structure and diversity. We found areas increasing in multifunctionality were likewise becoming more biologically and agriculturally diverse, without large losses in overall food production. This suggests the potential for complementarity among goals of food production, multiple ES, and biological and agricultural diversity for agricultural landscapes. While we cannot distinguish whether diversity is the driver, or the consequence, of ES multifunctionality, we can conclude that building diverse, multifunctional agricultural landscapes are an important goal for general system resilience and the future of food security

1. Introduction

Society's demands place a heavy, and at times conflicting, burden on agricultural landscapes. We want an increasing amount of food for everyone, stable and diverse markets to support farmer livelihoods, and the production of numerous non-food ES, all while minimizing biodiversity loss, reducing land conversion, dependence on water resources, and coping with an increasingly harsh and less predictable climate (United Nations, 2015; Landis, 2016). As such, improving food security, mitigating biodiversity loss and environmental degradation from agriculture, and conserving a diversity of ecosystem functions in agricultural landscapes are the major, intertwined challenges of our time (Bennett, 2017; Bennett et al., 2015). To date, research on these issues typically focuses on two outcomes: the delivery of food production, and its impact on biodiversity, and has thus somewhat neglected the complex

multifunctionality of agricultural landscapes (Wittman et al., 2017), including multifunctionality in agricultural landscapes as a viable choice to meet the needs of food production. A subset of research on agricultural landscapes has employed a social-ecological lens (Lescourret et al., 2015), which recognizes that the food production vs. nature conservation dilemma is shaped by key drivers with complex dynamics and feedbacks, and differ or interact across spatiotemporal scales (Fischer et al., 2015, 2017a; Wittman et al., 2017).

Agricultural landscapes are critical social-ecological systems, producing vital ES for multiple stakeholders (Mace et al., 2012). ES provided by agricultural landscapes include food production, carbon storage, water quality, soil fertility, and outdoor recreation (DeClerck et al., 2015). Enhancing the resilience, or the long-term capacity of the system to adapt to and shape change (Folke, 2006) of agricultural landscapes to produce ES that underpin human social and economic

well-being is thus an important goal (Biggs et al., 2012). Multiple aspects of the larger social-ecological system embedding agricultural landscapes influence the resilience of the production of services.

Estimating the resilience of social-ecological systems, and the sensitivity of resilience to changes in these systems, is limited by the practical evidence of empirical studies (Carpenter et al., 2005). While quantifying resilience itself is often tenuous or impossible given data limitations, it is possible to quantify some of those conditions of social-ecological systems responsible for building system resilience. This includes maintaining diversity and redundancy to provide options for responding to change and disturbances (Ehrlich and Walker, 1998; Elmqvist et al., 2003) and managing connectivity to facilitate recovery and restoration following disturbances (Biggs et al., 2012; Nyström and Folke, 2001).

To meet the demands of providing multiple ES, including food production, multifunctionality has become an increasingly central goal, particularly in agricultural landscapes. Managing agricultural landscapes (i.e., including both agricultural and other land types such as hedgerows, woodlots, wetlands, etc.) for multifunctionality provides a diverse range of ecosystem functions, services, and beneficiaries (DeClerck et al., 2015; Fischer et al., 2017b; Garbach et al., 2017). In addition, increasing multifunctionality of agricultural landscapes is believed to support self-regulating feedbacks and synergies that can maintain long-term productivity, ES provision, and resilience in an increasingly unstable world of environmental and socio-economic stressors (Gaudin et al., 2013; Khumairoh et al., 2012; Nyström et al., 2019; Peterson et al., 2018). In comparison, monofunctional agricultural landscapes wherein specialization and economies of scale have led to gains in productivity and efficiency (Peterson et al., 2018), come at the cost of environmental degradation (Tilman, 1999) and vulnerability to unpredictable stressors and change (Peterson et al., 2018; Rist et al., 2014).

Understanding which features of agricultural landscapes are related to multiple goals is a complex challenge. The potential for multifunctionality in these landscapes is restricted by the central goal of these areas to produce food, and the inherent tradeoffs between food production and ecosystem functions (Power, 2010). Additional goals include providing habitat for a diverse communities of other species (Wright et al., 2012) and place for human inhabitants to recreate, live, and work. The difficulties in identifying management goals for achieving multifunctionality is compounded by biophysical features, such as soil fertility and climate, which constrain multifunctionality yet are largely beyond human influence. Thus it is imperative to differentiate between extrinsic constraints and human-mediated actions relevant to implementing management and policies towards attaining multifunctionality.

Solution-focused research using ‘bright spots’, or the identification of areas that are performing substantially better than expected, is a promising new tool to meet such challenges inherent to researching and managing complex social-ecological systems. Exploring bright spots is an approach that has been used with great success in medicine and social sciences (Spreitzer and Sonenshein, 2004; Subbiah and Subbiah, 2015), and more recently in the fields of conservation (Cinner et al., 2016) and ES (Frei et al., 2018). The bright spot analysis first accounts for variation via a preliminary (null) model, followed by further pattern exploration of additional variables to identify associations between factors of interest at bright vs. ‘dark’ (i.e., areas performing substantially worse than expected) spots (Frei et al., 2018). As such, learning more from the factors influencing bright spots, as well as from areas growing ‘brighter’ over time, has the potential to highlight proven local solutions to complex societal problems (Levinson et al., 2007), that then can be used to inform policy and practice elsewhere.

In this paper, we empirically assess how areas changing in ES multifunctionality over time differ in multiple measures of diversity and connectivity in a complex agricultural landscape. To do so we (1) identify where ES multifunctionality is increasing more (brighter spots)

or less (darker spots) than predicted over time based on extrinsic constraints, (2) and compare how these areas have likewise changed over time for four measures of diversity (biological, agricultural, socio-economic, and landscape), as well as landscape connectivity.

2. Methods

2.1. Assessing temporal changes in multifunctionality

We used data on nine ES quantified by Renard et al. (2015) for 131 municipalities in southern Quebec, Canada, at 5-year increments from 1971–2006. ES included four provisioning (cattle, pork, poultry, and crops), two regulating (carbon sequestration and flood regulation), and three cultural services (hunting, campsites, outdoor activities); we used the temporal subset from 1982–1986 and 2002–2006 (for more details see Renard et al., 2015). We quantified ES multifunctionality separately for the two different time periods (1986 and 2006) by integrating the quantity of each service as well as its presence using the multiple ES landscape index (MESLI; Rodríguez-Loinaz et al., 2014) for each municipality, where a higher MESLI score means a greater provision of multiple ES (Frei et al., 2018; Table S1). We adjusted the MESLI slightly in order to highlight true multifunctionality (i.e., multiple services). The adjusted MESLI calculation is fully detailed in the supplemental information.

We created our null bright spots model to control for biophysical drivers of multifunctionality using generalized additive models (GAMs) with Gaussian distributions using the ‘*mgcv*’ package in program R version 3.4.2. to generate expectations of how ES multifunctionality was related to known abiotic environmental drivers such as soil and weather (Gaston, 2000; Mouchet et al., 2017). We used GAMs as opposed to generalized linear models as we had no *a priori* expectation that the relationships would be linear. We ran models for the two time periods (1986 and 2006) separately. We quantified seven variables, including: (1) the mean number of days (MeanGrowingDays) during the growing season (frost-free above 0 °C), (2) the mean precipitation (MeanGrowingPrecip) during the growing season, (3) the mean temperature (MeanGrowingTemp) during the growing season, (4) the dominant soil class in each municipality based on soil potential and limitations for agriculture (AgriCap), as described by Renard et al. (2015), (5) the average elevation (m) of the municipality (DEMmean), (6) the maximum elevation (m) of the municipality (DEMmax), and the area of the municipality (Area; km²). We tested for multicollinearity using variance inflation factor estimates in R using the ‘*car*’ package (Fox et al., 2017), which led to the exclusion of the DEMmean variable; all other covariates had inflation factor scores less than 5, indicating multicollinearity was not a serious concern. We created five *a priori* biophysical models for multifunctionality, including the: (1) Climate model (MeanGrowingDays + MeanGrowingPrecip + MeanGrowingTemp), (2) Soil model (AgriCap), (3) Elevation model (DEMmax), (4) Area model (Area), and Biophysical model (MeanGrowingDays + MeanGrowingPrecip + MeanGrowingTemp + AgriCap + DEMmax + Area) and ranked the models according to their model fit as measured by adjusted R². For both time periods the biophysical model explained the most variance of the tested models, explaining 50.7% and 52.8% of the variance for 1986 and 2006, respectively. Thus we used the biophysical models to calculate the predicted values for multifunctionality, and identified bright and dark spots for each time period as those municipalities that deviated by one or more standard deviation (SD) in multifunctionality (as measured by MESLI scores; Rodríguez-Loinaz et al., 2014) from the expected relationship determined by a null biophysical model (Frei et al., 2018). Further descriptions of the data and analysis used can be found in the supplementary information.

2.2. Temporal changes in species richness and functional diversity

We used presence/absence data for individual bird species from the

two Québec Breeding Bird Atlas (QBBA) in 1984–1989 (QBBA1) and 2010–2014 (QBBA2) to estimate functional species richness and dispersion. We followed the framework of Villeger et al. (2008), as well as the distance-based framework by Laliberté and Legendre (2010) to obtain a set of complementary metrics, including: (1) species richness, (2) functional richness, (3) and functional dispersion. We calculated functional metrics based on functional traits related to feeding behaviour and resource use as reported in the ELTONTRAITS 1.0 database (Wilman et al., 2014). Traits used in the functional metrics calculations included: diet composition (as percentages for 10 categories), foraging height preference (as percentages for seven categories), foraging activity period (binary as nocturnal or diurnal), and mass (grams; Table S2). Using this combination of traits, which account for both the foraging behaviour and the quantity of resources consumed by the species (Calba et al., 2014; Petchey et al., 2007), reflects the species' roles in the ecosystem (Luck et al., 2012; Schipper et al., 2016; Vetter et al., 2011). Diet composition and foraging height preference each included multiple categories; hence each category was included as a separate variable in the functional metrics calculations and weighed accordingly (i.e., 1/7 weight for foraging height preference). We calculated the functional metrics based on a Gower dissimilarity matrix using the function `dbFD` in the '`FD`' package (Laliberté and Legendre, 2010) in R. We tested for differences in each of the three metrics between the two time periods using Wilcoxon signed rank test in R. To quantify the temporal change in the three species metrics during the 20-year period between the two time periods we calculated the effect size for each metric for each municipality as:

$$ES_{M,x} = \frac{M_{x,QBBA2} - M_{x,QBBA1}}{0.5 \times (M_{x,QBBA1} + M_{x,QBBA2})}$$

where $ES_{M,x}$ represents the effect size for diversity metric M at municipality x , and $M_{x,QBBA1}$ and $M_{x,QBBA2}$ are the values calculated for diversity metric M at municipality x for the QBBA1 (1984–1989) and QBBA2 (2010–2014), respectively. This effect size quantifies a symmetrical index of increase or decrease between -2 and 2 (Bohning-Gaese and Bauer, 1996; Schipper et al., 2016). We tested for multicollinearity using variance inflation factor estimates in R using the '`car`' package (Fox et al., 2017), all metrics had inflation factor scores less than 5, indicating multicollinearity was not a serious concern.

2.3. Temporal changes in agricultural products and agrodiversity

As in Renard et al. (2016), we used the Canadian Agricultural Census to quantify the amounts of each agricultural product to calculate agrodiversity within municipalities across the Mont'ère'gie. We collected data from the 1986 and 2006 censuses on the production of four livestock species used for meat (pork, cattle, sheep, and poultry, comprised of chickens and turkeys), milk cows as an estimate of milk production, three perennial crops (fruit trees, grapes and berries, and hay), and six groups of annual crops (vegetables, wheat, oats, barley, maize, soybeans) (Table S1). Due to small changes in municipal boundaries in the 20-year period between the two census periods, we calculated the area of each municipality for each time period from digital boundary maps and quantified the agricultural products from each census as a per area measurement (i.e., animals per km², percentage of total area in cultivation) to render the values comparable between the two time periods. We ran a multivariate analysis using a distance matrix for differences between the agricultural products produced in the two time periods using the function `Adonis` with a Bray-Curtis dissimilarity matrix in the '`vegan`' package in program R (Oksanen et al., 2017).

To quantify agrodiversity, we standardized the agricultural products to unit variance (z-score) and calculated the Shannon diversity index (H'), which accounted for the richness and abundance of the 14 agricultural products for each municipality in both 1986 and 2006, using the diversity function in the '`vegan`' package (Oksanen et al., 2017) in R.

Similarly to Renard et al. (2016), we transformed the Shannon diversity index values into an effective number of agricultural products (ENAPs) following Jost (2006), where $ENAP = \exp^{H'}$. We tested for differences in ENAP between the time periods using Wilcoxon signed rank test in R. We quantified the change in agrodiversity over time by subtracting the ENAP in 1986 from the ENAP in 2006 for each municipality. As we made use of data from the Canadian Agricultural census to quantify ES multifunctionality and agrodiversity, specifically pork production was identical in the quantification of the two metrics; we wanted to ensure that the two indices were not collinear. We tested for collinearity between multifunctionality (MESLI) and agrodiversity (ENAP) using Pearson's pairwise correlation test in R for the two time periods separately. We found no collinearity between our multifunctionality and agrodiversity indices (Pearson's correlation coefficient 0.16 for 1986, 0.18 for 2006).

2.4. Temporal changes in social variables

We used the Canadian Agricultural Census and Canadian Census of Population to quantify 10 social variables to create two social diversity indices reflecting possible social changes in human demography and farm characteristics over time within municipalities across the Mont'ère'gie. We collected data from the 1986 and 2006 censuses on farm ownership (sole proprietor, family corporation, non-family corporation), farm size (small, medium, and large), farm operator age classes (under 35 years, 35–54 years, and over 55 years) and population density (Table S1). We used the ownership and farm size variable to quantify farm social diversity, and the farm operator age classes and population density variables to quantify demographic social diversity. Other social variables of interests, such as farm capital or percentage of farms with income from non-agricultural work, were difficult to compare over time periods due to extrinsic factors (e.g., sizeable inflation rates and variable changes in land prices across the study area) and inconsistency in reporting (e.g., income from non-agricultural work reported as percentage of farms during one time period, and as percentage of operators in the other time period). To quantify diversity, we standardized the 10 social variables to unit variance (z-score) and calculated the Shannon diversity index (H') for each of the social diversity indices (farm and demographic), which accounted for the richness and abundance of the social variables for each municipality in both 1986 and 2006, using the diversity function in the '`vegan`' package (Oksanen et al., 2017) in R. We tested for differences in both farm and demographic social diversity between the two time periods using Wilcoxon signed rank test in R. We also ran a multivariate analysis using a distance matrix for differences between the social variables in each of the indices in the two time periods using the function `Adonis` with a Bray-Curtis dissimilarity matrix in the '`vegan`' package in program R (Oksanen et al., 2017). Lastly, we quantified the change in both farm and demographic social diversity over time by subtracting the diversity index in 1986 from the diversity index in 2006 for each municipality.

2.5. Temporal changes in landscape structure and diversity

To quantify changes in landscape structure and diversity in our study area, we created land cover maps with supervised classification of Landsat satellite imagery of our study area for 1986 and 2011. Complete description of the imagery and analysis can be found in the supplementary information. Due to logistical constraints involved in creating detailed land cover maps, such as the need for ground truthing of land cover classification, the land cover maps we created for the two time period were simplified to four broad land cover classes: (1) Water, (2) Anthropogenic, (3) Forest/Natural, and (4) Agriculture/Grass. We used `Fragstats` version 4.1 (McGarigal et al., 2012) to calculate the following class and landscape variables for each municipality from the 1986 and 2011 land cover maps separately: (1) connectance index for forest/natural land cover (`ForestCONNECT`) using a 100 m threshold (from 0 to

100, where ForestCONNECT = 0 when there is just a single forest/natural land patch or no patches are connected within 100 m, and ForestCONNECT = 100 when all patches are connected), (2) landscape division index (DIVISION; from 0 to <1, DIVISION = 0 when the landscape consists of a single patch and reaches its maximum value when every cell is a separate patch), and (3) the Shannon-diversity of the landscape (SHANNON). We tested for differences between the time periods using Wilcoxon signed rank test with the stats in R. We quantified the change over time by subtracting the value of each variable from the 1986 time period from the 2011 time period. Complete descriptions for fragstats-derived variables can be found at <http://www.umass.edu/landeco/research/fragstats/fragstats.html>.

2.6. Temporal patterns of multifunctionality and possible features of resilience

To quantify changes in multifunctionality over time, we compared the status of each municipality (bright, dark or average spot) across the two time periods. If a municipality changed status between 1986 and 2006 we identified the directionality of the changes as a binary measure (brighter/darker) of change in multifunctionality. For example, if a municipality was identified as a dark spot in 1986 and an average spot in 2006, the municipality was growing 'brighter'. Likewise, if a municipality was identified as an average spot in 1986 and as a bright spot in 2006, the municipality was growing 'brighter'. Municipalities that remained in the same status between the two time periods were labeled as 'NoChange' for multifunctionality. We ran a multivariate analysis using a distance matrix for differences between the ES produced in the two time periods for municipalities growing 'brighter' and 'darker' over time using the function Adonis with a Bray-Curtis dissimilarity matrix in the 'vegan' package in program R (Oksanen et al., 2017).

We explored patterns of municipalities growing 'brighter' and 'darker' for multifunctionality over time in these two categories to multiple measures of diversity and connectivity over time as features of resilience, including: (1) avian species richness effect size, (2) functional avian species richness effect size, (3) avian functional dispersion effect size, (4) change in estimated agricultural products (ENAP), (5) the diversity of farm characteristics and human demographics in the area, (6) change in forest/natural area connectivity (ForestCONNECT), (7) change in landscape division (DIVISION), and (8) change in landscape diversity (SHANNON). We first tested these nine variables for collinearity using a Pearson's pairwise correlation matrix using the function ggcrr in the 'GGally' package in program R. All variables had low to moderate correlations (≤ 0.5) and were thus retained (Fig. S1). Lastly we tested for differences in each of the nine variables we quantified as features of resilience on the municipal scale in Montérégie, Québec, Canada, for areas growing 'brighter' and 'darker' for multifunctionality between 1986 and 2006 using Mann-Whitney tests in R.

3. Results

3.1. Species richness and functional diversity

All three metrics of avian species richness and dispersion significantly increased significantly over time for the study area (avian species richness p -value < 0.001, avian functional richness p -value < 0.001, avian functional dispersion p -value < 0.001; Wilcoxon signed rank tests). Specifically, species richness (mean effect size = 0.12; range = -0.14 - 0.35) and functional dispersion (mean effect size = 0.10; range = -0.07 - 0.30) increased slightly, and functional richness increased substantially (mean effect size = 1.99; range = 1.92-1.99).

3.2. Agrodiversity

While there was no significant difference for agrodiversity between the two time periods (p -value = 0.36; Wilcoxon signed rank tests), there

was a significant difference between the types of agricultural products produced in the region between 1986 and those produced in 2006 (p -value = 0.01; Adonis multivariate analysis of variance). Comparing the mean values across the study region for the 14 agriculture products used to quantify the ENAP, there were major changes in agricultural products produced by the region across the 20-year period. A majority of animal production declined, including poultry (70.7% decrease), cattle (38.0% decrease), and dairy cows (47.5% decrease), while pork (28.7%), and sheep (117.0% increase) production increased over the 20-year period (Fig. 1). Grain and hay production declined over the 20-year period, including declines in barley (70.5% decrease), oats (65.1% decrease), wheat (42.4% decrease), and hay (35.1% decrease), while maize (82.8% increase) and soybeans (5530% increase) increased dramatically, making these two crops by far the dominant agricultural crops in 2006 (Fig. 1). Other changes included fruit trees (35.7% decline), berries and grapes (488.5% increase), and vegetables (71.0% increase; Fig. 1), but overall represent small total agricultural land cover in the region.

3.3. Social diversity

Farm social diversity increased significantly between the two time periods (p -value < 0.001; Wilcoxon signed rank tests), in addition there is a significant difference between the farm social variables on the municipality scales in 1986 and those in 2006 (p -value = 0.01; Adonis multivariate analysis of variance). Specifically, the percentage of farms under sole proprietorship decreased, while the percentage of farms under family and non-family corporate ownership increased, and the number of small farms decreased while the number of medium and large farms increased.

Demographic social diversity decreased significantly between the two time periods (p -value < 0.001; Wilcoxon signed rank tests), in addition there is a significant difference between the demographic social variables on the municipality scales in 1986 and those in 2006 (p -value = 0.01; Adonis multivariate analysis of variance). Specifically, the number of farm operators under the age of 35 years old declined over time, while the number of farm operators between 35 and 54 years old, and the number of farm operators above 55 years old both increased over the 20 year time period. On average population density increased across the study area, with an average of 57 inhabitants per square kilometer in 1986, and 69 inhabitants per square kilometer in 2006.

3.4. Landscape structure and diversity

All three landscape metrics increased significantly over time between 1986 and 2011 in our study area (Fig. S2, including forest connectivity, landscape division, and landscape diversity (p -values < 0.001; Wilcoxon signed rank tests), meaning that the connectivity between forest/natural land patches increased, overall division or patchiness of the landscape increased, and that the diversity of the four land cover types increased at the municipal scale over time.

3.5. Changes in multifunctionality

Our analysis showed that 19 of 131 municipalities became 'brighter' and 24 of 131 municipalities became 'darker' for multifunctionality over the 20-year study period (Fig. 2). There was a significant difference in the ES produced in municipalities increasing in multifunctionality (brighter) between 1986 and 2006 (p -value = 0.02; Adonis multivariate analysis of variance); this change appears to be due to increases in flood regulation, hunting, outdoor activities, and pork production, with a slight decline in carbon sequestration and both crop and cattle production (Fig. 3). Similarly, there was also a significant difference between ES produced in municipalities decreasing in multifunctionality (darker) between 1986 and 2006 for (p -value = 0.05; Adonis multivariate analysis of variance); this change appears to be primarily due to a large decline in cattle production, with smaller declines in poultry and

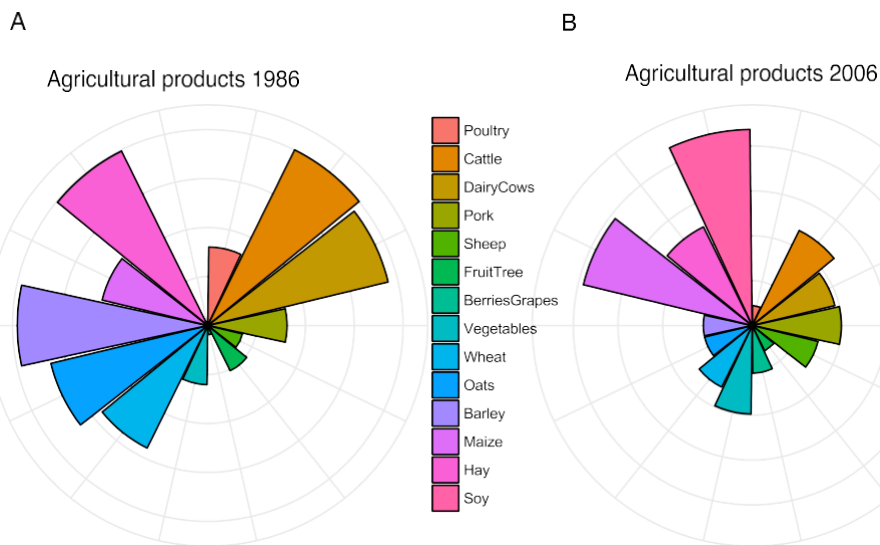


Fig. 1. Mean values for agricultural products for the study region in (A) 1986 and (B) 2006; each petal in the flower diagram is associated with an agricultural product used to quantify the estimated number of agricultural products (ENAPs). To facilitate comparison between products, all agricultural products values were standardized from 0 to 1 for the minimum and maximum agricultural products per area; as such, petals are comparable across bundles. Multivariate analysis concluded that the agricultural products produced in the two time periods were significantly different (p -value = 0.01; Adonis multivariate analysis of variance).

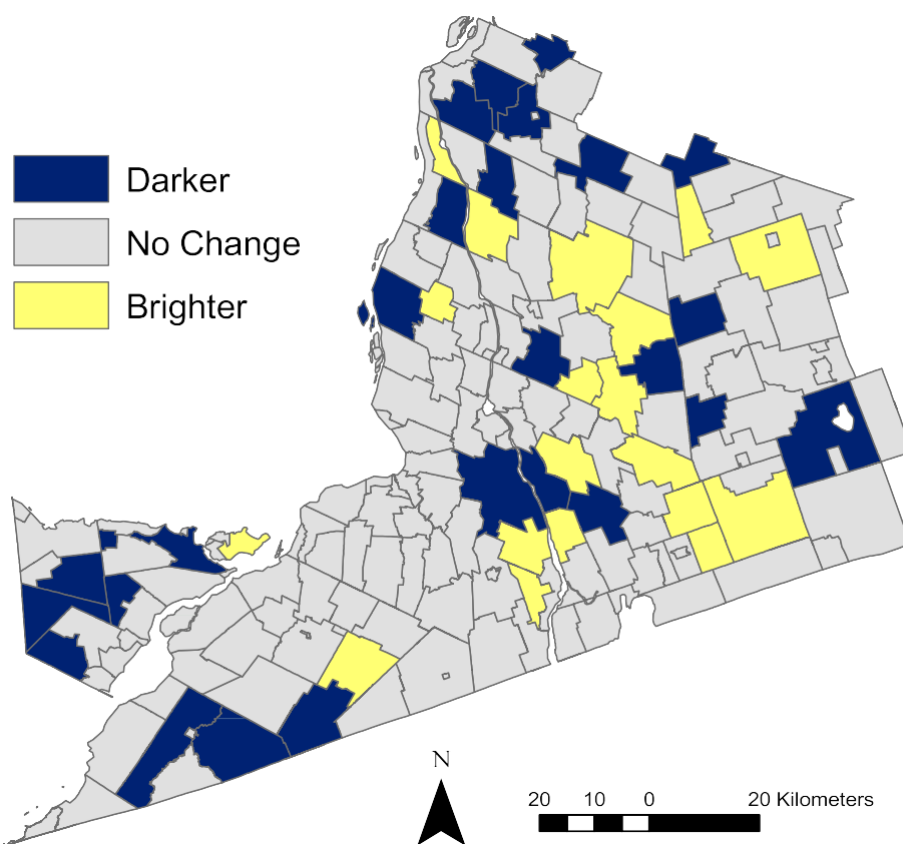


Fig. 2. Map of the Montérégie, Québec, Canada study area delineating areas growing 'brighter' and 'darker' for landscape multifunctionality, as quantified using the multiple ecosystem service landscape index (MESLI; Rodríguez-Loínez et al., 2014), for each municipality between 1986 and 2006.

pork production, and decline of outdoor activities (Fig. 3).

All three measures of change in avian species richness and dispersion over time were significantly different between municipalities becoming brighter and those becoming darker, with richness and dispersion increasing significantly more in those municipalities growing brighter between 1986 and 2006 (avian species richness, p -value = 0.005; avian functional richness, p -value = 0.001; avian functional dispersion, p -value = 0.033, Figs. 4 and 5). Similarly, change in agrodiversity, as measured by the change in ENAP over time, was significantly different between municipalities growing brighter and darker for

multifunctionality, with agrodiversity increasing significantly more in those municipalities growing brighter for multifunctionality between 1986 and 2006 (change in ENAP, p -value = 0.050, Figs. 4 and 5). In comparison, there was no significant difference between municipalities growing brighter and darker for multifunctionality and changes in the farm social diversity index (p -value = 0.672), the demographic social diversity index (p -value = 0.603), or the landscape structure or diversity for those municipalities over time, including forest connectivity (p -value = 0.750), landscape division (p -value = 0.325), and landscape diversity (p -value = 0.619, Figs. 4 and 5).

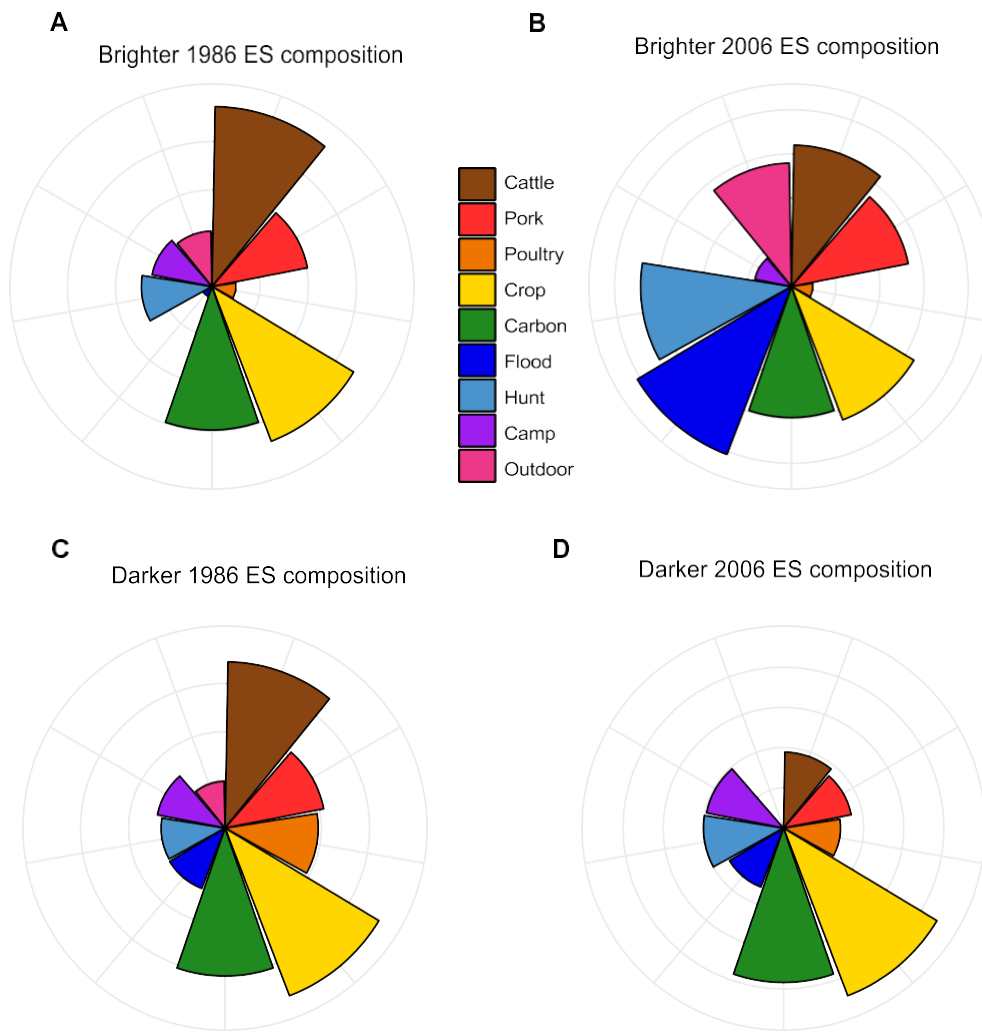


Fig. 3. Mean values for ecosystem services in (A) municipalities growing brighter for multifunctionality in 1986, (B) municipalities growing brighter for multifunctionality in 2006, (C) municipalities growing darker for multifunctionality in 1986, and (D) municipalities growing darker for multifunctionality in 2006; each petal in the flower diagram is associated with an ecosystem service to quantify the multifunctionality index (MESLI; Rodríguez-Loínez et al., 2014). To facilitate comparison between services, all ecosystem service values were standardized from 0 to 1; as such, petals are comparable across bundles. Multivariate analysis concluded that the ecosystem services produced in the two time periods were significantly different for both municipalities growing brighter (A and B; p -value = 0.02; Adonis multivariate analysis of variance), and darker for multifunctionality (C and D; p -value = 0.05; Adonis multivariate analysis of variance).

4. Discussion

4.1. Multifunctionality and features of resilient social-ecological systems over time

This study demonstrates that municipalities within an agricultural landscape becoming more multifunctional are also becoming more biologically and agriculturally diverse over the 20-year time period we investigated. This association supports the framework presented by Biggs et al. (2012), wherein diversity is a key feature of resilient social-ecological systems and their ability to produce multiple ES. In comparison, there is no relationship between areas changing in multifunctionality and measures of diversity and connectivity (social diversity, landscape diversity, and landscape connectivity) that we quantified during the same time period. This may be due to a number of factors, including the variables chosen to quantify the social and landscape variables, as well as the longer temporal rates of that these variables act upon. Our findings provide empirical evidence of the potential for agricultural landscapes to meet multiple goals, such as increased ES multifunctionality (including food production), agricultural diversity and biological diversity, enhancing the resilience of the system and the future of food security.

While previous work suggested that bright spots for biodiversity and ES multifunctionality in agricultural landscapes were neither spatially congruent or in conflict at a single scale of time (Frei et al., 2018), this study suggests that areas where multifunctionality is improving over time are likewise growing more diverse. Specifically, agricultural

landscapes exceeding expectations for ES multifunctionality are growing in both in the diversity of their avian species community and agricultural products produced in the region, given a relatively short time period of 20 years. While we cannot distinguish whether biological and agricultural diversity are the drivers, or the consequence, of areas exceeding expectations for multifunctionality in agricultural landscapes, we can conclude that these areas growing in ES multifunctionality are important for building resilience in social-ecological systems, as they support increases in multiple aspects of diversity (Ehrlich and Walker, 1998; Elmqvist et al., 2003)). Ultimately, this research highlights complementary goals for land managers and policy makers striving for resilient agricultural landscapes, which support the provisioning of multiple ES, agricultural diversity, and avian species diversity.

4.2. Avian diversity increasing with time and in more multifunctional landscapes

The increasing avian species richness and functional diversity in our study area is similar to trends seen across North America in the last four decades (Barnagaud et al., 2017). Changes in biodiversity often vary non-linearly over time and with strong scale-dependency, challenging the identification of underlying environmental drivers (Barnagaud et al., 2017; Korhonen et al., 2010; McGill et al., 2006). The poleward shifting of bird species has been demonstrated across North America (La Sorte et al., 2007), as well as specifically in areas directly adjacent to our study area in eastern North America (Zuckerberg et al., 2009). Thus, we suspect that increases in species richness and diversity in our study area

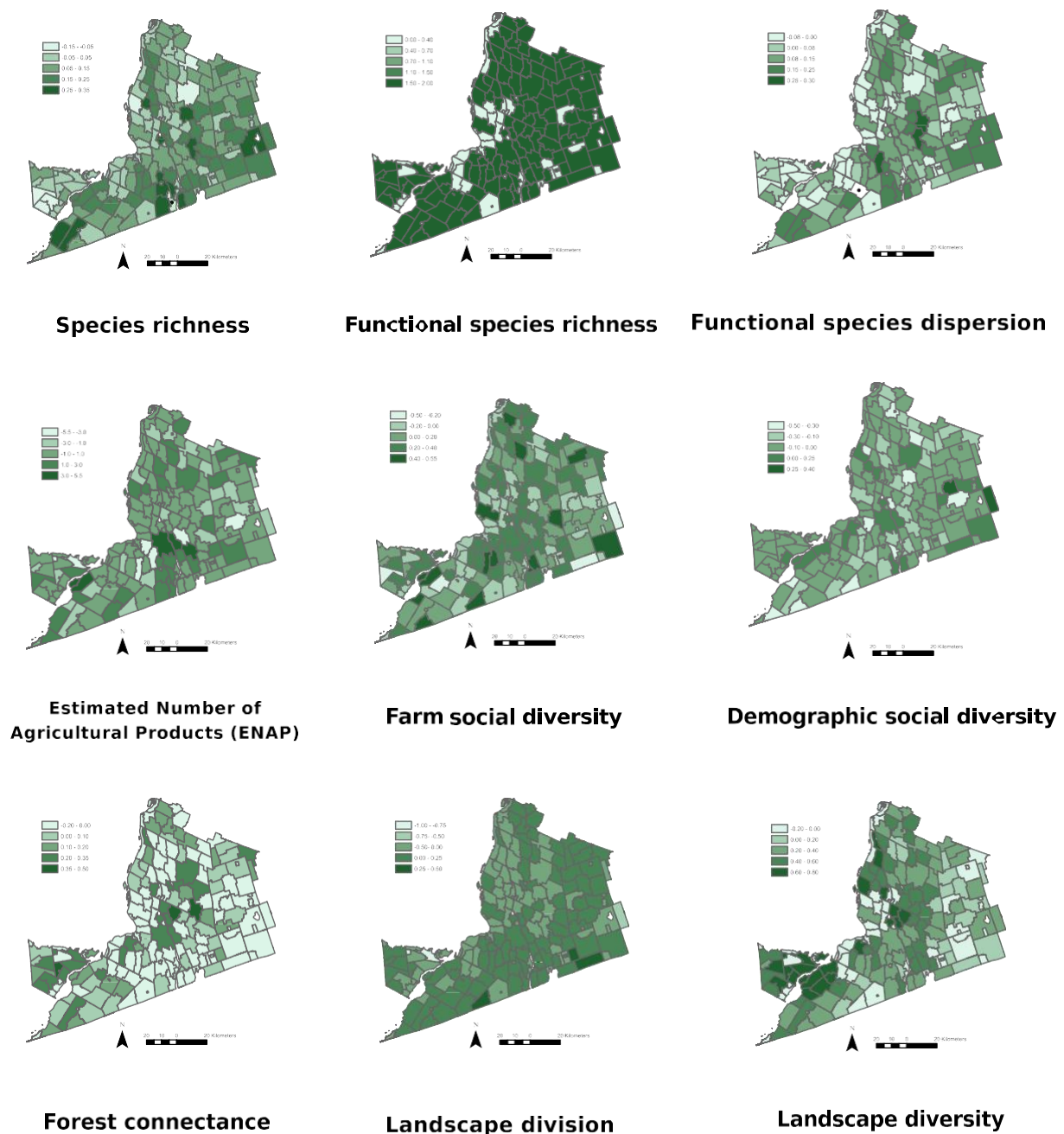


Fig. 4. Map of the Mont'ere'gie, Qu'ebec, Canada study for the change over time of nine features of resilience that were quantified across the region within the agricultural landscape between 1986 and 2006, including: (1) avian species richness, (2) avian functional richness, (3) avian functional dispersion, (4) estimated number of agricultural products (ENAP), (5) farm social diversity, (6) demographic social diversity, (7) forest/natural area land cover connectance index (100 m threshold), (8) landscape division index (100 m threshold), and (9) landscape diversity (Shannon diversity index).

could be the result, at least in part, to the northern movement of southern bird species between our two time periods. In addition, changes in the landscape, such as reforestation of lower fertility agricultural lands following the collapse of the milk industry, or the increasing land under cereal crops in the most productive areas (Domon et al., 1993), might additionally be responsible for bird community turnover due to radical changes in habitat availability for different species groups.

We found all three measures of avian richness and diversity over time to be significantly higher in areas growing more multifunctional than expected over time, compared to those growing less multifunctional. This suggests that areas within the agricultural landscape growing more multifunctional, not only had a greater increase in species richness over

time, but that the bird species found in these areas were functionally more diverse and disperse (i.e., the spread of species in functional space; Lalibert'e' and Legendre, 2010). Functional richness and dispersion are associated with greater ecosystem function (Mace et al., 2012; Steudel et al., 2016), hence supporting the theory of maintaining species diversity as important for building system resilience by providing options for responding to change and disturbances via a wealth of ecological functions (Elmqvist et al., 2003).

4.3. Multifunctional areas are concurrently growing in agricultural diversity

We found that while the agrodiversity index we quantified (ENAP)

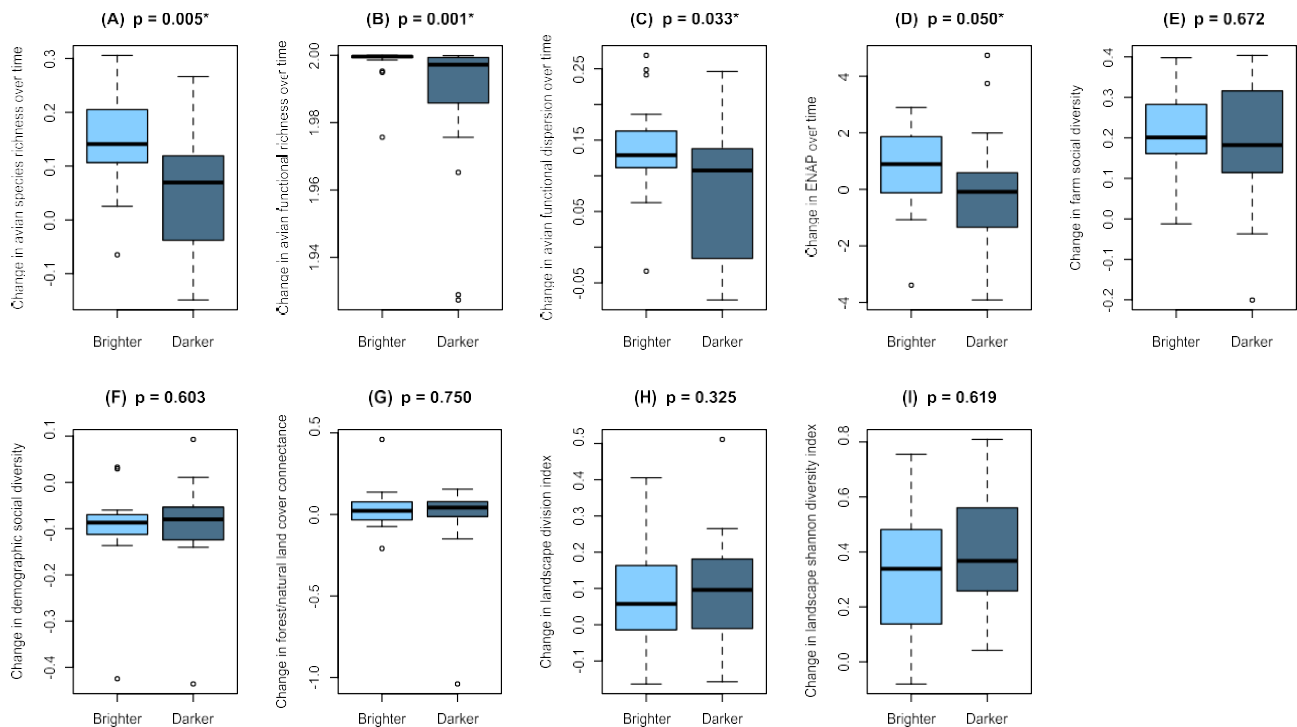


Fig. 5. Differences in the features of resilience on the municipal scale in Montérégie, Québec, Canada, for areas growing ‘brighter’ and ‘darker’ for ecosystem service multifunctionality between 1986 and 2006 for changes in (A) avian species richness between 1984–1989 and 2010–2014, (B) avian functional richness between 1984–1989 and 2010–2014, (C) avian functional dispersion between 1984–1989 and 2010–2014, (D) estimated number of agricultural products 1986 and 2006, (E) farm social diversity in 1986 and 2006, (F) demographic social diversity in 1986 and 2006, (G) forested/natural land cover connectivity between 1986 and 2011, (H) landscape division between 1986 and 2011, and (I) landscape diversity between 1986 and 2011. *p*-values determined using Mann-Whitney tests.

did not change significantly on a municipal-scale between our two time periods, the underlying composition of the agricultural products used to quantify agrodiversity showed significant turnover. In particular, maize and soybean production, the two main cash crops currently produced in the area, increased dramatically between the two time periods. Previous research at a larger spatial scale in our study area demonstrated that the greatest increase in agrodiversity occurred between the 1960s – to the early 1990s, resulting from a shift from hay and oats to cash crops and high-value livestock (Renard et al., 2016). Diversification during this time was driven by stagnation in demand for milk production coupled with provincial government initiatives promoting diversification of agriculture to gain self-sufficiency, particularly regarding grain production (Domon et al., 1993). Yet not all areas increased similarly, with the greatest increase in cash crop production occurring in areas with the most fertile soils (Domon and Bouchard, 2007; Renard et al., 2016).

During the 20-year time period of substantial agricultural turnover, areas growing more multifunctional than expected were concurrently growing more agrodiverse, compared to areas growing less multifunctional. Previous research concluded that areas underperforming for multifunctionality within the agricultural landscapes were those dominated by agricultural production, specifically crop production (Frei et al., 2018). Thus, the inherent tradeoff between increased crop production at the cost of other ES could lead to monofunctional landscapes, while bright spots for multifunctionality occur when such tradeoffs are more balanced, producing a greater diversity of ES (Frei et al., 2018). Our findings showing the associations between agrodiversity and multifunctionality over time suggests that managing for a diversity of agricultural products aid in balancing tradeoffs that lead to monofunctional landscapes, and thus encourage multifunctionality at a landscape scale. It is important to note that we found that areas growing more multifunctional than expected were not simply doing so as result of a dominant loss of food production in favor of other ES instead areas growing in multifunctionality maintained the ES of food provisioning

while increasing other services, particularly regulating and cultural services (Fig. 3).

4.4. Social diversity changing with larger farms and ageing farm operators, not with the multifunctionality of the landscape

The social diversity indices (farm and demographic) we quantified differed significantly across the Montérégie during the 20-year period of our study, as did the composition of the underlying 10 social variables. The increase in diversity for the farm social diversity was primarily driven due to the turnover between a decrease in farms under sole proprietorship and respective increases in family and non-family corporate ownership, and a similar decrease in small farms and increase in medium and large farms. Conversely the ageing population of farm operators and resulting change in the age structure of farm operators in the study region over time led to an overall decrease in demographic social diversity. This pattern is on par with the general trend of larger farms and ageing farm operators seen across Canada, where average farm area increased from 598 to 778 acres, and the average age of farm operators rose from 47.5 to 54.0 years between 1991 and 2011 (Beaulieu, 2014).

Despite the differences seen over time in the two social diversity indices, there was no difference in either farm or demographic social diversity between areas growing brighter and darker for multifunctionality. Previous work details the relationships between multifunctionality and socio-economic variables in a static timeframe, including multifunctionality bright spots associated with smaller farm size and dark spots associated with larger farm size and capital, increased mechanization and agricultural inputs (Frei et al., 2018). This highlights the need for continued interdisciplinary research on the social, economic, and ecological factors driving multifunctionality in agricultural landscapes.

4.5. Landscape structure and connectivity

Landscape structure is inherently tied to the capacity and flow of ES to its beneficiaries (Eigenbrod, 2016), particularly within agricultural landscapes (Power, 2010), and the provisioning of multiple ES (Mouchet et al., 2017). Landscape structure and diversity significantly changed in the 20-year period across our study area, increasing in connectivity between forested or natural land cover types, as well as more patchy and diverse overall. As such we were surprised that there appears to be no relationship between the changes in the structure and diversity of the landscape, and changes in the multifunctionality of the landscape. We postulate that this lack of relationship might be due to several reasons. First, the strength of this relationship depends the definition of desired multifunctionality, which vary widely between regions and stakeholders (Manning et al., 2018). Thus, the relationship between ES multifunctionality and forest/natural area connectivity would have been very different if our definition of multifunctionality would include fewer agricultural ES and more forestry-based services. Second, there are many different metrics that could be used to quantify landscape structure, such as patch size, shape, edge, etc.; alternative measures of landscape structure could have given differing results. Lastly, certain measures, such as landscape diversity, might be associated with the presence of land cover types that provide limited or little additional ES, such as anthropogenic land cover. The use of more complex land cover maps including different forest types, wetlands, shrublands, and other more nuanced natural and anthropogenic land cover types might have resulted in a stronger relationship with the provision of multiple ES, and remains a future research need.

4.6. Multifunctionality and variability among temporal frameworks

One important final caveat that we were unable to address in this research, or the data used, is the inherent hierarchical nature of ecosystems and variability in temporal scales of the natural processes therein (Klijn and Udo de Haes, 1994). Ultimately, our findings that areas changing in ES multifunctionality over time also had changes in biological and agrodiversity, but not in the landscape and social dynamics, may be due to the inherent temporal speed that these variables act upon. Biological diversity has the potential to swiftly track ecosystem changes, particularly among species with high dispersal capabilities such as birds (Parmesan, 2006). Likewise shifting demands of local or global food markets with changing diets or incomes (Tilman and Clarke, 2014) can influence the agricultural products produced in a region relatively swiftly. For example, Morton et al. (2006) reported that areas deforested for cropland in Brazil between 2001 and 2004, were directly correlated with the mean annual soybean price in the year of forest clearings occurred. While the 20-year time period we examined in this study was an appropriate time scale to measure changes in biological diversity (for an vagile animal species) and agricultural diversity, it might be too short a time period for inherently slower variables such as landscape dynamics that include reforestation and social dynamics that include human ageing or changes in farm ownerships and operations.

5. Conclusions

Managing agricultural landscapes for ES multifunctionality, including multiple facets of food production as well as regulating and cultural services, enables the dual goals of feeding the world and conserving a diversity of ecosystem functions. We found areas increasing in multifunctionality over a relatively short time period were likewise becoming more biologically and agriculturally diverse, without large losses in food provisioning ES. Future research on the relationship between multifunctionality and other features of social-ecological systems, such as social and landscape dynamics, should endeavor to look across the longer timeframes that these slower variables are acting on. The findings of this study support previous work highlighting that bright

spots for multifunctionality occur when tradeoffs between crop production and other ES are more balanced than those in monofunctional landscapes (Frei et al., 2018). Generally, our research suggests the potential of complementary goals for stakeholders and land managers seeking to increase ES multifunctionality, as well as biological and agricultural diversity, to build a brighter future for resilient agricultural landscapes in many forms.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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