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Research, part of a Special Feature on Ecosystem Service Trade-offs across Global Contexts and Scales

Ecosystem service trade-offs, perceived drivers, and sustainability in contrasting agroecosystems in central Mexico

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ABSTRACT. The ability of agroecosystems to provide food ultimately depends on the regulating and supporting ecosystem services that underpin their functioning, such as the regulation of soil quality, water quality, soil erosion, pests, and pollinators. However, there are trade-offs between provisioning and regulating or supporting services, whose nature at the farm and plot scales is poorly understood. We analyzed data at the farm level for two agroecosystems with contrasting objectives in central Mexico: one aimed at staple crop production for self-subsistence and local markets, the other directed to a cash crop for export markets. Bivariate and multivariate trade-offs were analyzed for different crop management strategies (conventional, organic, traditional, crop rotation) and their underpinning socioeconomic drivers. There was a clear trade-off between crop yield and soil quality in self-subsistence systems. However, other expected trade-offs between yields and soil quality did not always occur, likely because of the overall good soils of the region and the low to medium input profile of most farms. Trade-offs were highly dependent on farm-specific agricultural practices; organic, traditional, and rotation management systems generally showed smaller trade-offs between yield and soil quality, pest control, and biodiversity than did conventional management systems. Perceived drivers reported by farmers included increasing prices for cash crops, rising costs of inputs, and extreme climatic events (e.g., drought, hail, frost). Farmers did not identify the regulation of soil quality, water quality, soil erosion, pests, or pollinators as important constraints. Although acceptable yields could be maintained irrespective of key regulating and supporting services according to these perceptions, current levels of soil erosion and nutrient runoff are likely to have important negative effects at the watershed scale. Sustainability in both agroecosystems could be increased substantially by promoting alternative practices aimed at maintaining biodiversity, soil quality, and soil retention.

Key Words: *agroecosystems; avocado; ecosystem services; maize; Mexico; trade-offs*

INTRODUCTION

The analysis of the trade-offs between the goal of maximizing crop yield and the regulating and supporting services that underpin land productivity is more important than ever as humans deal with increasing food demand and the strong environmental impacts of agroecosystems (Bennett and Balvanera 2007, Zhang et al. 2007, Raudsepp-Hearne et al. 2010, Foley et al. 2011). Key services to agroecosystems include the regulation of soil fertility, erosion, and pests, as well as the maintenance of the agrobiodiversity that directly or indirectly modulates yields, such as pollinators. In turn, agroecosystems can have negative effects on other ecosystem services, as is the case with water quality (Tilman et al. 2002, Zhang et al. 2007, Keeler et al. 2012). Much work is still needed to understand how the nature of these trade-offs changes among agroecosystems.

The nature of the trade-offs between yield and the regulating and supporting services that sustain yields are likely to change with the intensity and type of management. A growing amount of literature is currently showing that conventional farming systems differ from organic ones along various dimensions, including yield, water quality, agrobiodiversity maintenance, and climate change mitigation (Power 2010, Gomiero et al. 2011, Kremen and Miles 2012). In particular, diversified farming systems contribute to increases in agrobiodiversity, soil quality, carbon sequestration, water-holding capacity in surface soils, energy-use efficiency, as well as resistance and resilience in the face of climate change (Kremen and Miles 2012). Nevertheless, further systematic assessment of the trade-offs in conventional and organic agroecosystems is still pending.

Assessing trade-offs in agroecosystems can rely on pairwise comparisons as well as on multivariate evaluations of a range of services. Pairwise comparisons are quite useful to understand the nature of the relationship between two selected services (Bennett et al. 2009, Raudsepp-Hearne et al. 2010). In contrast, multivariate assessments contribute to a better understanding of the complexities involved in trade-offs among multiple services and the identification of bundles of services (Raudsepp-Hearne et al. 2010). These two assessment strategies are complementary and allow for a more holistic and integrated assessment of the trade-offs at stake.

Trade-offs among services and their consequences for the sustainability of agroecosystems do not depend solely on the biophysical conditions operating at the plot level but also on the perceptions of the people managing them (Gregory 2000, Maass et al. 2005, Balvanera et al. 2011, Martín-López et al. 2012). Local stakeholders hold strong perceptions about the critical drivers that underpin changes in desired services and, in particular, on those related to yield, that are essential for decision-making. For example, farmers in Ghana are aware that management factors such as crop diversification and planting of short-season varieties, biophysical conditions such as soil fertility, and societal conditions such as access to extension services, credit, and land tenure strongly determine their ability to adapt to climate change and sustain yields (Fosu-Mensah et al. 2012). Such perceptions need to be assessed systematically for a range of contrasting agroecosystems and management conditions to provide information on how local decisions are made that may alter, define, and shape productive ecosystems.

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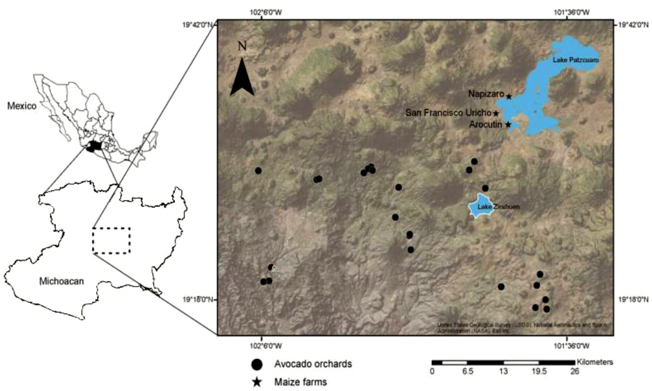
Here, we analyzed two contrasting agroecosystems in central Mexico: maize produced for local, subsistence consumption, and avocado produced mainly for export. The questions posed for each of the systems were: (1) Are there trade-offs between yield and agrobiodiversity and between yield and key regulating and supporting services? (2) How do multivariate trade-offs between agrobiodiversity and provisioning, regulating, and supporting services change between alternative management regimes? (3) What are the key drivers perceived by local farmers and key informants that underpin changes in yield? Based on our analyses, we then discuss how sustainable these systems are in terms of productivity and the maintenance of associated ecosystem services. We then identify and discuss the main issues that need to be considered to build pathways toward sustainability.

THE CASE STUDIES

The study area is the P'urhépecha plateau, in the State of Michoacán, Mexico. There, millenary, self-subsistence, maize-based agroecosystems coexist with highly profitable, input-intensive avocado orchards focused on export production that have recently and rapidly expanded over maize agriculture and forested land (Bravo-Espinosa et al. 2014; Fig. 1). Traditional maize production and intensive avocado production occupy neighboring areas sharing similar biophysical conditions. Socioeconomic conditions also remained largely similar until the expansion of avocado production, which has very different objectives in terms of production, markets, and distribution of benefits. We think that the original similarities between maize and avocado production allow them to be a useful comparison.

Fig. 1. Location of the study cases in Michoacán, central Mexico.



Traditional maize production in the Pátzcuaro Lake watershed

The Pátzcuaro Lake watershed is located within 19º25'–19º45' N and 101º25'–101º54' W, at 2000–2800 m above sea level, and has mean annual rainfall of 987 mm (Bravo-Espinosa et al. 2009). The temperate climate and fertile volcanic soils (acrisols, luvisols, and andosols) have allowed highly productive maize-based agriculture for at least 3000 years (Astier et al. 2010). This agriculture was critical to the splendor of the P'urhépecha culture until the Spanish colonization. In this region, Púrhépecha culture and language are still deeply rooted in the present population of approximately 128,000 people (Marr and Sutton 2004). The colonial city of Pátzcuaro and the impressive landscape of the lake make the region one of the most important tourist destinations in Mexico.

The traditional *milpa* agroecosystem involves maize, beans, and squash intercropping and is still present in the watershed, although monoculture is now widely practiced. Most of the produce is self-consumed as food or fodder or is sold regionally. *Milpa* agroecosystems are only one of the multiple productive activities on which farmers depend (Astier et al. 2005). Livestock (mainly cattle, equines, and poultry) were introduced by the Spaniards and brought an element of diversity to the system. The conifer and oak forests in the upper parts of the watershed are managed communally and provide numerous timber and nontimber goods. Artisanal pottery, brick production, fisheries, and tourism complete the livelihoods of the rural population.

The varying conditions across the watershed have resulted in considerable genetic diversity. Astier et al. (2010) identified and mapped the distribution of six maize landraces and their hybrids, which are specifically associated with particular biophysical conditions (altitude, soils, and water regime), management practices, and sociocultural (i.e., culinary) uses.

The use of agrochemicals and fossil energy is still relatively minor. However, synthetic fertilizer use has been increasing with the adoption of maize monoculture. Nutrient loss and soil erosion from the upper parts of the watershed have caused eutrophication of the lake, decreasing fisheries productivity and diminishing the landscape and recreational values. Poverty, migration, low wages, and low crop prices have led to the abandonment of agricultural land and a reduction in the contribution of agricultural activities to the local economy compared to past decades.

To evaluate how trade-offs between agrobiodiversity and provisioning, regulating, and supporting ecosystem services change with management regime, we first identified three management options: conventional, traditional, and crop rotation. In the conventional system (CS), plowing and sowing are mechanized. Insect pests (*Phyllophaga* spp. and *Diabrotica* spp.) and weeds are controlled using chemical pesticides. Fertilization is conducted using increasing amounts of synthetic fertilizers. Grain harvesting is carried out manually in December, whereas straw is harvested between April and May.

In the traditional system (TS), beans and squash are established together with maize (*milpa*), and fertilized with animal manure. Animal traction is used for soil preparation and sowing. Weed and insect pest control is performed manually, although chemical pesticides are used occasionally. A recent innovation to increase fertility is the use of semi-mature compost (using dung and plant material). A growing conversion from conventional back to traditional farming is occurring in response to the increasing costs of synthetic fertilizers and low maize prices, with some farmers becoming more environmentally aware of the effects of agrochemical use.

The rotation system (RS) was originally designed for fodder production. Animal traction is used for plowing and sowing, and summer maize is rotated with legumes established from fall to spring. The legumes are often common vetch (*Vicia sativa*), broad bean (*Vicia faba*), and pea (*Pisum sativum*), with the first used as fodder and the others for human consumption. A recent innovation promoted by local nongovernmental organizations is the use of green manure, with about 30% of legume straw plowed into the soil and the remainder cut for fodder. No synthetic fertilizer is applied, and weed control is performed mechanically with oxen.

The green gold of Michoacan: intensive avocado production in the Uruapan region

Avocado (*Persea americana* Mill.) is native to Mexico and has been cultivated since pre-hispanic times. Large-scale production for export only began in the mid-1960s. The first commercial orchards were established around the city of Uruapan. However, recent decades have seen an exponential growth in the area cultivated for avocado, from 13,000 ha in 1974 (Morales-Manilla and Cuevas 2011) to > 130,000 ha in 2010 (Servicio de información agroalimentaria y pesquera de la Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación: http://www.aguacate.gob.mx/index.php?portal=aguacate) to satisfy the export market. Mexico is now the top world producer and exporter of avocado, contributing 28% of the world's production in 2010. The Uruapan region produces 86% of the national production, which makes this particular region the largest world producer. Avocado is largely sold in USA, the European Union, and Japan, and there is also a growing national market.

Land-use change for avocado production has taken place at the expense of maize crops and native pine and oak forests; it has contributed to increased greenhouse gas emissions, water pollution, and eutrophication (Bravo-Espinosa et al. 2014). Land use for avocado orchards increased from 3 to 34% in area, whereas annual crops (including maize) decreased from 35 to 16% and forests from 47 to 30% within the main avocado growing area (Morales-Manilla and Cuevas 2011, Morales-Manilla et al. 2012; L. M. Morales-Manilla and G. Bocco, Centro de Investigaciones en Geografía Ambiental, UNAM, *personal communication*). Large growers have high use of external inputs, high incomes, and are up to date with the latest technologies for fertilization, irrigation, pest and disease control, and post-harvest management. They use manure in combination with synthetic fertilizers. Large growers co-exist with more traditional, small-scale growers.

There is also a burgeoning, but much smaller sector, of certified organic export growers. They also use many external inputs such as cattle manure and the latest commercial developments for organic fertilizers and biological pest control. Organic farmers usually allow the presence of other plant species, although organic monocultures can also be found.

A strong cooling and packing industry has been created along with the growth in production and exports. In contrast with maize, avocado has been highly profitable, has a dynamic and competitive market, generates numerous temporary jobs with good wages, and is widely promoted by official programs.

METHODS

Choice of ecosystem services and related indicators

Agricultural output (yield) was chosen as the indicator of the key provisioning service at the farm scale. The indicators chosen to evaluate regulating services were: soil quality, regulation of soil erosion, and pest regulation. Agrobiodiversity indicators included crop diversity, herb functional diversity, and richness of avocado pollinators.

Maize

Napízaro, Uricho, and Arocutin are located at the lower part of the Pátzcuaro Lake watershed (2100 m above sea level), between 19°36"00' N, 101°43"00' W and 19°33"00' N, 101°42"00' W, and surrounded by undulating topography. The climate is temperate, with an average annual rainfall of 1040 mm, falling mainly in June to October (five months). Temperatures range between 6.1°C and 24.1°C. However, the climatic variability found in the second year of this study challenges the average trend of the last 40 years, with minimum temperatures 5°C lower than normal and 30% less rainfall. The first and third years of this study had average rainfall (1220 and 820 mm, respectively), whereas the second year was considered as a dry year (678 mm).

We selected four farms for each contrasting agricultural system (conventional, traditional, crop rotation). The dominant soils are Acrisols, which are acidic (pH 4.5–6), with high cationic exchange capacity (approximately 30 cmol/kg), and rich in sesquioxides and clays (65–70%). They are relatively poor in soil organic carbon (SOC < 18 mg C/g) and total nitrogen (Nt < 1.6 mg N/g; Pajares Moreno and Gallardo Lancho 2010). The sites were chosen to minimize variability among them and thus encompass only the first of four main agricultural landscapes that correspond to different soil classes and moisture regimes (Mapes et al. 1991, Astier et al. 2010): (1) *temporal,* or strictly rainfed lands (mainly including Acrisols and Litosols); (2) *humedad,* or residual moisture lands (including Andisols); (3) *riego,* or irrigated lands; and (4) *jugo,* or the land at the lakeshore. Also, Napízaro, Uricho, and Arocutin are representative of the communities in the region where agriculture and livestock constitute the main economic activities (Astier et al. 2010). Farms included in this study had used the same type of management (conventional, traditional, crop rotation) for at least three years.

Direct measurements in the crop plots and personal interviews were conducted in 2010 and 2011. The nonprobability quota method (Casal and Mateu 2003) was used to select individual farms; 12 farms and their crop plots were chosen to represent each of the management systems while ensuring similar soil and climatic conditions. Each of the 12 fields were hosted by one farmer, as suggested by Ngwira et al. (2012). All trials were managed by the farmers with the support of technicians who provided recommendations regarding homogeneous input doses and the general management of the fields.

Crop yield: Grain yield was measured in four 1.4 × 5-m quadrats per plot and expressed in unit weight per area (ton/ha). The reference value was the optimum regional yield according to interviewed farmers and key informants.

Soil quality: Maintenance of soil quality is essential to maintain acceptable yields. Soil organic matter (SOM), pH, and cation exchange capacity (CEC) were selected as indicators of soil quality. Samples were taken from the upper 15 cm of mineral soil within the plots and from adjacent forest and shrubland sites to provide reference values for "nonagricultural" soils, although such areas are subject to intensive grazing and burning. Soil pH was measured in 1:10 soil:water solution shaken for 30 min. SOM was determined by the Walkley-Black method (Walkley and Black

1934), and CEC was estimated using the method of the Mexican Official Norm (SEMARNAT 2002). Soil erosion was not considered as an indicator in maize systems because the evaluated sites were on flatlands that had no apparent erosion problems.

Pest regulation: Phyllophaga spp., a root-eating moth larva, is one of the main insect pests affecting maize in the region. It can reduce yields by up to 15% (Morón 1986) and is the most important maize pest (Pérez-Agis et al. 2008, Arnés et al. 2013). The number of *Phyllophaga* spp. individuals per volume of soil (individuals/m³) was measured monthly over a 6-mo period comprising the rainy season (June–November) by taking four random soil samples per plot and counting all individuals (Pacheco et al. 2008). The reference value used for this variable was 0–7.4 insects/m³. At numbers above this value, *Phyllophaga* spp. is considered a pest, and conventional farmers apply insecticide in September, the month with the highest insect population (Ruiz et al. 2006).

Crop diversity: Crop diversity is a key feature of the agrobiodiversity within agroecosystems that strongly determines yield and other regulating services. High crop diversity, as opposed to monoculture, has been shown to contribute to improved biological control, carbon sequestration, soil fertility, and pollination. Crop diversification can often reduce the abundance of insect pests that specialize on a particular crop while providing refuge and alternative prey for natural enemies (Altieri 2002, Gomiero et al. 2011). This is particularly true for predators of *Phylophaga* spp., as shown by Pérez-Agis et al. (2004) in a similar farming context and region. Crop diversification may favor wild pollinators (Power 2010). SOM and soil fertility can be maintained or even increased with an adequate spatial and temporal rotation design (Tilman et al. 2002, Astier et al. 2005), as has been shown for the Acrisols of Michoacán (Gallardo et al. 2005). The indicator is the number of species grown within a given year cycle; five was the maximum richness observed in any of the three management systems evaluated.

Avocado

Orchards within the municipalities of Uruapan, Pátzcuaro, Salvador Escalante, Ario de Rosales, and Tacámbaro were located within a 50 km radius of 19°12’00” N, 101°42’28” W and within an altitudinal range of 1500–2400 m above sea level. Orchards were included in the study based on the willingness of farmers to provide information and allow sampling. We selected farms from a pool of 17 conventional and 19 organic farms to obtain a balanced number of conventional and organic farms and the equitable inclusion of young (< 10 yr), mature (10–20 yr), and old (> 20 yr) orchards within each type of management. The number of replicates included in each analysis depended on the variable. Replicates for soil fertility and agrobiodiversity variables were restricted by time and cost. Analyses of yield were constrained by the availability of data from participating farmers.

Crop yield: Annual yields were obtained from interviews with the managers or owners of 15 orchards. Avocado fruits can be maintained on the trees for several months and harvested partially or completely when the grower decides to do so. Therefore, there can be zero to several harvests within a calendar year. It is worth mentioning that avocado yields are treated as confidential data, and although average trends are available as general statistics, actual yields are difficult to obtain for specific orchards. Considering these restrictions, we tried to include the average yield for several years whenever possible. We gathered data for up to five years in nine orchards and for two years in six orchards. The maximum yield reported among the group of orchards was used as the reference value for this indicator.

Soil erosion: Soils in this region are deep and rich but tend to be lost at high rates when forest is removed and replaced by avocado orchards. Soil loss was measured during the rainy season (June–October) in 28 orchards in 2011 and 22 orchards in 2012. Soil traps were built as described by Robichaud and Brown (2002). Traps were also placed in four adjacent *Pinus*-*Quercus* forest patches to determine a reference value for soil erosion under native vegetation without management. To estimate the proportion of soil that had been retained from the original forested soils in orchards, soil profiles were examined in soil trenches excavated in eight orchards and in nearby forest patches. The trenches were located under avocado or forest trees, and soil depth was determined by examining soil layers and the presence of fine roots.

Soil quality and impacts on water quality: Excessive use of agrochemicals is likely to affect soil quality and has been shown to decrease the quality of nearby water bodies. Three soil parameters were measured as indicators of soil quality and the potential for groundwater pollution. Soil pH, nitrate, and phosphate were measured in five conventional and five organic orchards, and in five adjacent forest sites in July 2010 and 2011. Three soil samples were taken from the upper 15 cm of mineral soil in two positions, one under the canopy and the other outside the canopy or as far from the trunk as possible for five trees per orchard.

Soil pH was measured in 1:10 soil:water solution shaken for 30 min. Soil nitrate was extracted with 2N KCl and soil phosphate with Mehlich III solution and determined colorimetrically with a Braun+Luebbe Autoanalyzer (Technicon Industrial System 1997). Because fertilization in orchards is carried out right on the canopy or under the trunk, we used the values obtained outside the canopy as references to evaluate changes induced by fertilization. Values outside the canopy were also compared to forest values and confirmed to be within a similar range.

Herb functional diversity: Herb functional diversity in avocado farms is an indicator of the diversity of species that are potentially available to attract pollinators. Total plant species richness and the dicot/monocot ratio were used as indicators of total and functional diversity. Plant species richness was measured in the 36 orchards in 2011 and in 10 selected orchards in 2012. Approximately one-half of the orchards were organic and one-half conventional. Herb species richness was estimated from five 1-m² plots located in the corners of a zig-zag transect. Given that the presence of other woody species was rare in orchards, both species richness and functional diversity indexes were centered in herbs. A functional diversity index was constructed focusing on pollinator attraction and was estimated as the ratio between dicot (predominantly attractive flowers) and monocot (predominantly unattractive flowers) species. The reference values for both variables were obtained from similar measurements made in six forest sites.

Richness of avocado pollinators: The richness of avocado pollinators is an indicator of the maintenance of the native insect community and its potential contribution to avocado pollination. Pollination by a diverse community of wild pollinators has been shown to be more stable than that dependent on a single introduced species (Kremen and Miles 2012). The richness of avocado flower visitors was measured in five organic and five conventional farms. Avocado flower visitors were collected at each farm from 10 trees for 10 min every hour from 9:00 to 18:00 at two flowering periods (2010–2011 and 2011–2012). Specimens were preserved for avocado pollen examination and were identified when possible. The reference value used for this variable was the maximum number of avocado pollen-carrier species registered in these orchards.

Trade-offs and drivers assessment

Bivariate and multivariate trade-offs
We explored the bivariate trade-offs between yield and one or more key regulating services. We chose SOM for the case of maize, and soil erosion and nitrate and phosphate concentrations (negative effects of fertilizer use) for the case of avocado. However, the small sample size and high variability among farms did not allow for statistical tests.

We assessed multivariate trade-offs for the contrasting management systems for both maize and avocado using multiradial diagrams constructed with all of the indicators and response variables standardized to the noted reference values. In the case of avocado, forest values were used as reference for soil quality and herb functional diversity indicators.

Perceived drivers
We interviewed farmers and key informants (technicians, farmer advisors, heads of institutions, and academic experts) for each agroecosystem to understand their perceptions of the biophysical and socioeconomic drivers that underpin the described trade-offs. All owners of the maize and avocado farms sampled were interviewed. In the case of maize, a highly recognized farmer and a researcher from the region were selected as key informants. In the case of avocado, the three heads of the Local Plant Health Councils to which the orchards belong were the key informants. The topics of the interviews included yields, inputs, pests and diseases, climatic conditions, and potential responses to changes in costs and prices. The same set of closed questions was posed to all interviewees to identify the drivers based on frequency of responses.

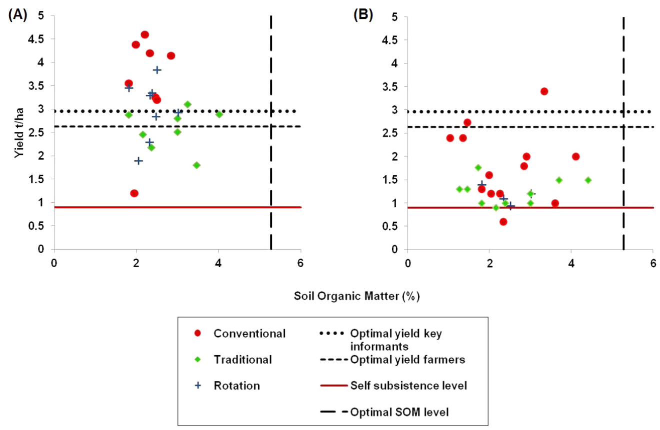
RESULTS

Bivariate trade-offs

Maize
For maize, there was a trade-off between maximizing yield and the regulation of soil quality, measured as SOM content (Fig. 2A). This pattern was found for the year with average precipitation. Conventional farms consistently showed higher yields but lower levels of SOM, whereas traditional farms presented lower yields but higher SOM. Farms in the rotation system showed intermediate levels for both variables. Average yields in the conventional system were 35% higher than in the traditional system and 18% higher than in the rotation system.

Conventional farms produce yields that are generally higher than optimum levels in the region, according to farmers and key informants, in years with average rainfall. In contrast, traditional farms produce yields that are within or close to optimum levels. SOM levels showed more variation across traditional farms, with some farms having low levels similar to those of their conventional counterparts. Some traditional farmers interviewed described lower yields as an effect of ceasing to use synthetic fertilizers, and thus, as a result of the transition back to the traditional system. Indeed, traditional farmers with higher SOM levels acknowledged that after an initial period of yield loss, production had reached near-optimum levels along with increased SOM, and might continue to do so.

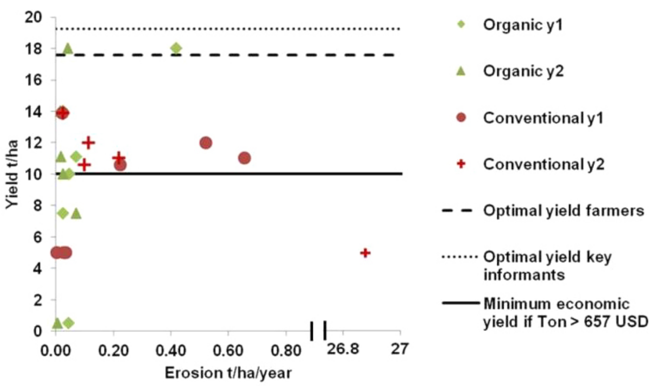
Fig. 2. Trade-offs between maize yield and soil fertility in the Pátzcuaro Lake watershed, Mexico. (A) Average year. (B) Dry year.



Dramatic decreases in yield were found in the dry year (Fig. 2B). Almost all farms, including the conventional farms, produced yields below optimum levels. Most critically, the dry year rendered yields close to or even below self-subsistence conditions. Longer time series are required to assess long-term changes and variations in response to extreme weather conditions.

Avocado
We found no clear trade-offs between yield and the regulation of soil erosion for avocado (Fig. 3). Annual erosion rates measured in some avocado farms were nevertheless higher (0.2–0.65 ton/ha) than those measured in the forest (0–0.014 ton/ha) for many farms; nevertheless, soil erosion was highly variable among farms, depending on orchard design. One farm showed extremely high erosion (27.65 ton/ha) that could have resulted from inadequate management practices. Open canopy orchards with full herb cover had virtually zero losses, whereas closed canopy orchards with no herbs registered the largest losses. Because of this variability, there were no significant differences between conventional and organic orchards or between forest and orchards. However, forests never exceeded 0.02 ton/ha, and only one organic orchard exceeded 0.2 ton/ha, whereas six conventional farms showed erosion > 0.2 ton/ha. There were also no clear differences in yields between organic and conventional orchards. This can be attributed to the high use of fertilizers (mainly cattle manure) in some organic orchards. Smaller farms with fewer resources tend to use lower external inputs, regardless of the management system.

Fig. 3. Trade-offs between avocado yield and soil erosion in avocado agroecosystems on the P'urhépecha plateau, Mexico.

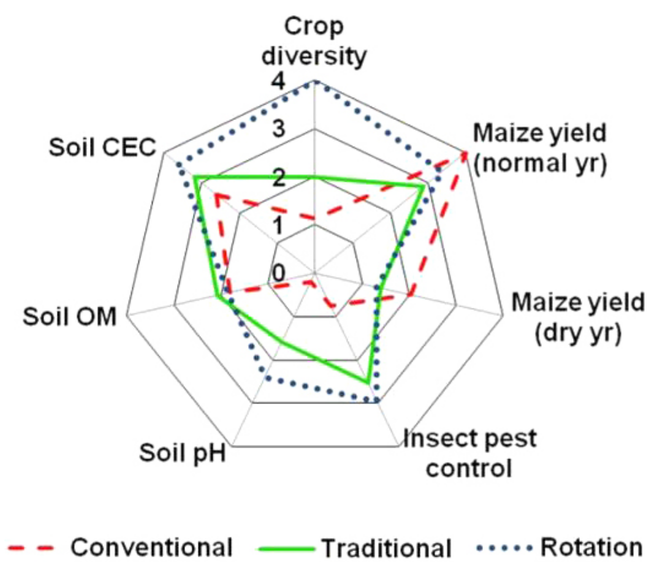


Multivariate trade-offs

Maize

Conventional, traditional, and rotation management differed in the multivariate assessment of soil quality and pest control indicators (Fig. 4). Crop rotation with higher crop diversity generally showed higher values for most of the regulating and supporting services. Traditional farms showed intermediate values of these services. Yield increases occurred at the expense of clear reductions in regulating and supporting services for the case of conventional farms. The differences were small, however, possibly due to the combined use of chemical fertilizers, manure, and composted materials in the conventional plots.

Fig. 4. Multivariate trade-offs in maize agroecosystems in the Pátzcuaro Lake watershed, Mexico. CEC = cation exchange capacity, OM = organic matter.

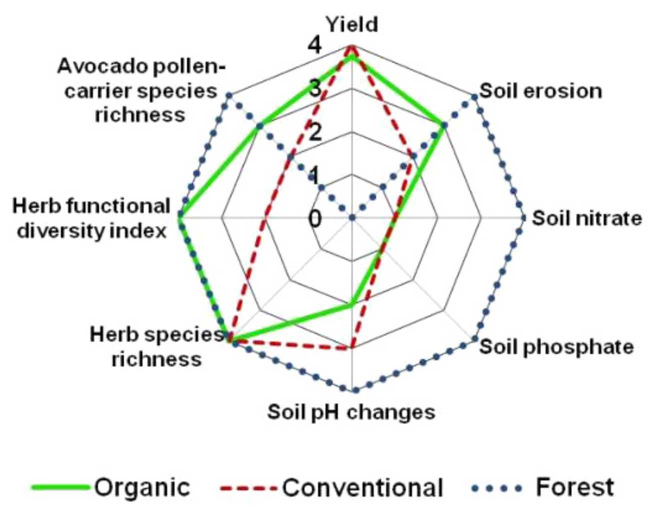


Conventional farms used insecticides on a regular basis for *Phylophaga* spp. control. In contrast, it is likely that the lower pest incidence in traditional and crop rotation farms is due to the higher availability of organic matter from both manure and straw, making maize roots less attractive to pests.

Avocado

Conventional and organic farms differed in the multivariate assessment of soil quality, herb functional diversity, and richness of avocado pollinators (Fig. 5). Organic orchards showed smaller trade-offs between yield and the maintenance of regulating and supporting services (erosion control, soil quality, and agrobiodiversity maintenance). Herb species richness was similar in organic and conventional orchards to that of forest sites. Herb species richness is likely promoted by increased light and nutrient availability and thus determined by canopy size and distribution, rather than management system.

Fig. 5. Multivariate trade-offs in avocado agroecosystems in the P'urhépecha plateau, Mexico.



In terms of herb functional diversity, forest sites and organic orchards contained on average four times more dicot than monocot species. In contrast, this ratio was close to one for conventional orchards. It is likely that excessive herb trimming in conventional orchards favors monocots.

The number of avocado pollen carriers was highest in forests, followed by organic farms, and was lowest in conventional farms. The use of herbicides is rare, so this pattern is likely due to the abundance dicots, which are attractive to pollinators. The number of insects visiting avocado was higher for organic than for conventional farms. *Apis mellifera* was overwhelmingly dominant over native pollinators. Therefore, herb presence in orchards is likely to be essential for the maintenance of the main pollinator (*A. mellifera*) during the long periods when avocado flowers are absent.

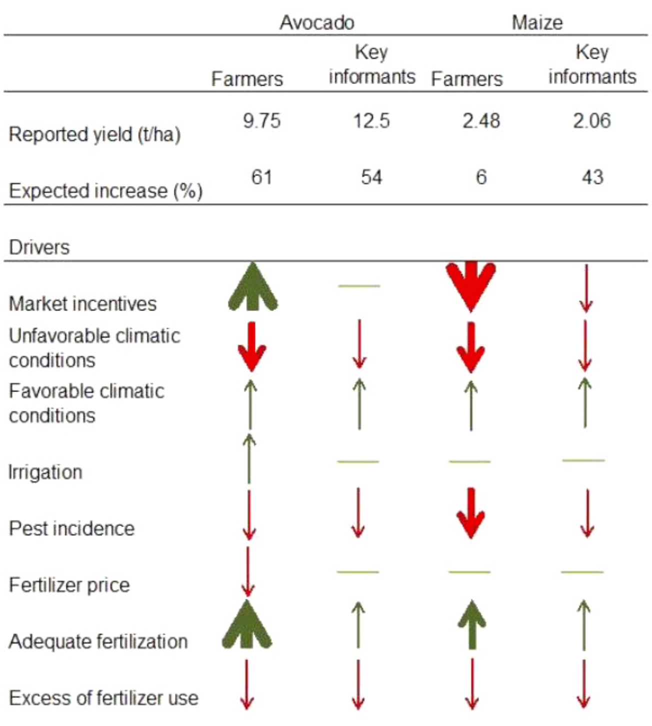
All orchards showed altered soil chemistry with virtually no ammonium and 10–100 times more nitrate and phosphate under avocado canopies than in forest sites. The nitrate and phosphate levels vastly exceeded the needs of the avocado trees and are therefore potential groundwater pollutants. Fertilizers have also altered soil pH (up or down) by one unit.

Perceived drivers

Maize

Market incentives were the most important driver perceived by farmers to act as a deterrent for maize production (Fig. 6). Although maize prices have increased recently in line with world prices, the rising costs of inputs, particularly synthetic fertilizers, cannot be compensated. Conventional growers sell their maize as forage, which has a lower price than maize for food from improved varieties. Traditional farmers sell *criollo* (local landraces) maize in local markets at one-third of the price obtained in regional and global markets. Some maize growers mentioned the pressure to convert their maize systems into avocado orchards given the high prices for avocado.

Fig. 6. Perceived drivers underpinning yield in maize and avocado agroecosystems. Arrow width reflects frequency of responses (smallest to widest: zero [dash], ≤ 30%, 30–50%, ≥ 50%). Green = positive association, red = negative association.



Climatic conditions and fertilizers, both synthetic and organic, were also very important drivers underpinning current yield conditions (Fig. 6). Unfavorable climatic conditions can drive yields down. Fertilization such as occurs on conventional farms can increase yields; however, over-fertilization is considered a key driver of soil degradation in those systems.

Avocado

Market incentives were also the most important driver motivating avocado production, although in this case fostering increases in yield. Avocado prices have been rising over the last 15 years in response to the increasing demand for exports. Such price increases have stimulated the use of agrochemicals, despite their rising costs and environmental impacts, to ensure high yields. Accordingly, agrochemical use was reported to be a key driver. Unfavorable climatic conditions were highlighted as an important driver of yield reductions.

DISCUSSION

We found moderate trade-offs between maize yields and the regulation of soil fertility, but no trade-offs between avocado yield and the regulation of soil erosion. While these patterns could suggest that the production systems are sustainable, it is likely that they rather reflect the biophysical conditions and the management history of the region. Soils in the region are deep and fertile as a result of their recent volcanic origin. Maize might constitute an example of sustainable management, as soils have been farmed over thousands of years while maintaining SOM at acceptable levels. This is particularly true for the traditional and crop rotation systems, whereas some of the conventional farms with > 10 years of intensive management showed lower SOM levels. In contrast, decreases in SOM and increased soil erosion are clearly occurring in the case of avocado, although the magnitude of the total accumulated loss is still relatively low compared with the original condition, given the young age of most orchards. Soil loss values observed here (< 0.2 ton ha^{-1} yr^{-1}) are acceptable if compared to estimations of soil formation found in the literature (0.4–2 ton ha^{-1} yr^{-1} for volcanic soils; Li et al. 2009). If we use these values as a reference, most of our measures would be considered acceptable (Bravo-Espinosa et al. 2009). However, recent studies have mentioned the need to include not only soil formation rates and crop yields, but also other environmental issues (such as agrochemical, cultivation, and irrigation tolerance) and off-site effects to make fair judgments (Li et al. 2009).

Important trade-offs between yield and potential impacts on water quality were found for avocado. High fertilizer rates are probably influencing high nitrate and phosphate concentrations in the sampled soils. However, water runoff and accumulation in streams is very likely to carry these nutrients and have a strong negative effect on water circulation and quality. Indeed, Morales-Manilla and Cuevas (2011) reported high phosphate levels (0.2–5 mg/L) in nearby streams collecting water from areas with extensive cover of avocado orchards. These levels exceed by far the standards for human consumption (0.1 mg/L), making untreated water suitable only for agricultural/aquacultural use. Further assessments, including the effects of physical conditions (e.g., slope) and the surrounding landscape are therefore needed.

The analysis of multivariate trade-offs allowed us to explore important interactions among provisioning, regulating, and supporting services. High yields from conventional maize farms are heavily dependent on fertilizer use and have negative effects on the regulation of soil quality and erosion. Similarly, intensive production of avocado is associated with elevated soil loss, reduced soil quality, effects on water quality, and a reduction in herb and pollinator diversity. Traditional and rotational maize systems and organic avocado showed higher levels of regulating and supporting services than intensive systems. Although negative effects on key regulating and supporting services would be expected to undermine yields (Zhang et al. 2007), we did not find any such tendencies within the time frame of this analysis.

Crop price, climatic conditions, and fertilizer use were the drivers that were most consistently perceived to underpin changes in yield for both maize and avocado. Low prices for *criollo* maize have been deterring efforts toward increasing yields, whereas increasing prices for avocado have placed strong pressure toward increasing those yields. Climate change is perceived in the region as an important threat; changes in the temporal patterns of precipitation and an increased frequency of drought are risk factors, and are consistent with observations and predictions by government agencies (Conde et al. 2004). Decreased yields in dry years threaten food security for maize and reduce income from avocado. Fertilizers are perceived in both agroecosystems to increase yields at the expense of soil quality.

Although direct measurements could have allowed more accurate estimation of services and agroecosystem biodiversity, indirect measurements such as those used here constitute useful indicators that can be measured easily and understood by relevant stakeholders. One important caveat is that static proxies were used to assess flows. For example, the number of larvae was used as an indicator of pest regulation; although fewer larvae would indicate better regulation, an ideal indicator would take into account the actual dynamic regulation processes. Similarly, higher levels of nitrates might be associated with higher runoff to adjacent water bodies, but actual flows were not measured.

Our analysis highlights various challenges facing the exploration of trade-offs among services within agroecosystems. The first challenge is the need to assess a range of services and indicators of these services. Key, well-known indicators such as SOM, soil erosion, and nutrient content have often been assessed (Speelman et al. 2006, Astier et al. 2011). However, we found declines in agrobiodiversity-related supporting services and changes in yield under different climatic conditions, which should be taken into account more systematically.

The second challenge is that of the spatial and temporal scale of analysis. We focused here at the farm level; this approach allowed us to link the different services to a particular farm. However, the variance among farms was not assessed and likely contributes to the small differences among management regimes found here. Trade-offs also occur at landscape scales, at which soil erosion and the use of fertilizers affect water quality. Also, the different services analyzed here operate at different spatial scales. Yields are produced yearly for maize and up to twice per year for avocado, but soil formation and soil erosion operate at the scale of hundreds or thousands of years. The fact that most avocado and conventional maize farms are quite recent therefore obscures the assessment of the trade-offs among services. Interactions between both agroecosystems also need to be taken into account. Maize farmers have been selling manure, normally used to fertilize their fields, to avocado growers for the last five years. This management practice could contribute to higher yields in avocado at the expense of SOM in maize. At present, most studies of trade-offs among services have been undertaken at a single spatial scale (Nelson et al. 2009, Raudsepp-Hearne et al. 2010), although assessments of some interactions across scales have begun (Laterra et al. 2012).

The use of proxies may allow for long-term participative monitoring of many regulating and supporting services, and larger sample sizes. Spatial and temporal patterns would then be revealed through time for an increasing number of sites. Also, involving stakeholders in monitoring has been shown to have positive effects in changing management practices (Vaidya and Mayer 2014). Participatory monitoring with coarse-scale indicator approaches would need to be complemented by long-term experimental assessments in controlled sites and the use of more precise indicators. The types of resources and infrastructure needed for such experiments were previously available in Mexico under the national agricultural research institute (INIFAP), but have now been largely reduced (Reyes 2013).

The third challenge is collating biophysical assessments of these trade-offs with those of people's perceptions of the trade-offs and the drivers that underpin them. Farmers and key informants did not recognize the degradation of maize and avocado agroecosystems with respect to the regulating and supporting services as key drivers underpinning changes in yield. The interviewees, for instance, attributed most of the changes in yield to changes in climatic conditions and the increasing use of fertilizers. As a consequence, conventional growers will continue pushing their systems to maximize yields independently of the decrease in soil quality and the loss of agrobiodiversity. As Jackson et al. (2007) note, increasing agrobiodiversity in agriculture is only partially related to the maintenance of ecosystem services at the farm level, although farmers do not tend to perceive the "external" benefits of conservation at wider scales. At present, analyses of the perceptions of services and their interactions (Castillo et al. 2005, Martín-López et al. 2012) are often separate from those dealing with the biophysical quantification of services; further research is needed at the intersection of these variables.

The fourth and final challenge is in explicitly linking the assessment of trade-offs and people's perceptions with that of system sustainability and its consequences on the long-term maintenance of ecosystem services. We found higher trade-offs between ecosystem services in conventional systems compared to traditional, rotation, or organic systems. Nevertheless, in avocado systems, some trade-offs were more influenced by specific practices than by the management system itself.

Traditional and rotation maize agroecosystems derive from millenary knowledge and have been apparently sustainable for several hundreds of years (Toledo et al. 2003), but are decreasingly favored by the prevailing socioeconomic conditions of the region. Conversely, conventional systems emerged recently and are heavily influenced by the technologies promoted by federal and state programs and credits. In contrast, organic avocado systems, which showed smaller trade-offs between yield and regulating and supporting services, are currently favored by specialized markets and not by farmers' convictions. Both maize and avocado systems seem to be highly vulnerable to droughts, and thus, to climate change. Therefore, a comprehensive framework linking ecosystem services maintenance and sustainability assessments is needed that includes trade-offs among services, historical conditions that have contributed to current ecosystem state, as well as the role of biophysical and societal drivers on long-term ecosystem performance.

CONCLUSIONS

We analyzed maize and avocado agroecosystems in central Mexico. We found trade-offs between maximizing yield and the regulation of SOM in maize, and some evidence of trade-offs between yield and regulation of soil erosion in avocado. We found that conventional intensive production systems showed stronger negative effects on soil quality and amount, water quality, and agrobiodiversity than did traditional, rotation, and organic production systems. Farmers attributed most changes in yield to market incentives, climatic changes, and fertilizer use, rather than most of the identified trade-offs.

Our study contributes to the literature on trade-offs among ecosystem services by documenting the characteristics of two contrasting agroecosystems of Mexico, and also by highlighting some of the challenges associated with such research. Systematic assessment of multiple services at multiple spatial and temporal scales, people's perceptions of these services and their associated drivers, and their linkages to current dominant socioeconomic drivers are needed to further assess threats and opportunities toward sustainability.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/6875

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