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Cite this article: Tamburini G, De Simone S, Sigura M, Boscutti F, Marini L. 2016 Soil management shapes ecosystem service provision and trade-offs in agricultural landscapes. *Proc. R. Soc. B* **283**: 20161369. http://dx.doi.org/10.1098/rspb.2016.1369

Received: 16 June 2016
Accepted: 4 August 2016

Subject Areas:
ecology, environmental science

Keywords:
agriculture intensification, conservation tillage, crop yield, nitrogen fertilization, pest control, soil fertility

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Electronic supplementary material is available at http://dx.doi.org/10.1098/rspb.2016.1369 or via http://rspb.royalsocietypublishing.org.

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Soil management shapes ecosystem service provision and trade-offs in agricultural landscapes

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Agroecosystems are principally managed to maximize food provisioning even if they receive a large array of supporting and regulating ecosystem services (ESs). Hence, comprehensive studies investigating the effects of local management and landscape composition on the provision of and trade-offs between multiple ESs are urgently needed. We explored the effects of conservation tillage, nitrogen fertilization and landscape composition on six ESs (crop production, disease control, soil fertility, water quality regulation, weed and pest control) in winter cereals. Conservation tillage enhanced soil fertility and pest control, decreased water quality regulation and weed control, without affecting crop production and disease control. Fertilization only influenced crop production by increasing grain yield. Landscape intensification reduced the provision of disease and pest control. We also found tillage and landscape composition to interactively affect water quality regulation and weed control. Under N fertilization, conventional tillage resulted in more trade-offs between ESs than conservation tillage. Our results demonstrate that soil management and landscape composition affect the provision of several ESs and that soil management potentially shapes the trade-offs between them.

1. Introduction

Considering the growing demand for agricultural goods worldwide [1], there is a strong need to identify farming practices able to maintain high levels of productivity while minimizing detrimental effects on the environment [2]. Hence, studies exploring the effects of different farming practices on multiple ecosystem services (ESs) are urgently needed.

Soil management has been shown to affect belowground properties linked to multiple ESs. Tillage for example is a widespread practice, valuable for optimizing soil conditions for seed germination and crop growth, and for controlling weeds and pests. However, a large body of research has demonstrated how intensive (conventional) tillage can lead to soil-related problems such as erosion, loss of soil fertility and deterioration of habitat for beneficial organisms such as earthworms and predatory insects [3]. Conservation tillage is an alternative farming practice able to minimize the negative effects of tillage operations on the soil environment. This tillage system is characterized by non-inversion of soil combined with a permanent vegetation cover. Conservation tillage has been shown to improve general soil quality (e.g. increased soil organic matter (SOM) content, reduced surface run-off and leaching of nutrients, and improved soil structure), and soil biodiversity [4]. However, the adoption of conservation tillage can also result in unwanted outcomes such as increased weed abundance, reduced yield, increased risks of disease incidence and phosphorus leaching [5]. To maximize crop production, another widely adopted soil management practice is the use of inorganic fertilizers.

Table 1. Ecosystem services and the relative indicators considered in the study.

ecosystem service	service symbol	service indicator	model[a]
crop production		grain yield (kg of wheat/barley grain m^{-2})	$Y \sim$ till $\times$ fert $\times$ land, random = pair ID/field ID, family = normal
disease control		disease incidence (% of infected leafs per 50 leafs recorded by two visual counts)	logit(Y) $\sim$ till $\times$ fert $\times$ land, random = pair ID/field ID, family = normal
soil fertility		soil organic matter content (%)	$Y \sim$ till $\times$ land, random = pair ID, family = normal
water quality regulation		phosphorus saturation (% of soil binding sites already occupied by P)	$Y \sim$ till $\times$ land, random = pair ID, family = normal
weed control		weed species richness (number of weed species)	$Y \sim$ till $\times$ fert $\times$ land, random = pair ID/field ID, family = normal
		weed cover (% of soil covered by weeds)	logit(Y) $\sim$ till $\times$ fert $\times$ land, random = pair ID/field ID, family = normal
pest control		predator abundance (per 50 tillers by two visual counts)	$Y \sim$ till $\times$ fert $\times$ land + aphid, random = pair ID/field ID, family = Poisson
		aphid parasitism (% parasitized aphids per 50 tillers by two visual counts)	logit(Y) $\sim$ till $\times$ fert $\times$ land + aphid, random = pair ID/field ID, family = normal

[a]Y = response variable; explanatory variables are till (tillage: conservation versus conventional), fert (fertilization: 0 versus 80 kg of N ha^{-1}), land (landscape: proportion of semi-natural habitats at 0.5–1 km or arable land at 0.5–1 km radius around fields), aphid (aphid density on 50 tillers). Family normal indicates general mixed-effects models while family Poisson indicates generalized mixed-effects models.

Beside direct effects on crop yield, fertilization may modulate the effects of different tillage systems on the provision of supporting and regulating ESs [3,6]. Moreover, fertilization imposes higher production costs and it can cause environmental impacts such as enhanced greenhouse gas emissions, increased disease incidence, pest performance and eutrophication of water bodies [7]. Although the effects of different soil management strategies on the provision of single services have been reported (e.g. tillage on erosion and pest control [8,9]; nitrogen fertilization on pest pressure and pollination [10]), studies exploring potential repercussions on multiple ESs are scarce.

Along with local management at the field scale, landscape composition plays a key role in shaping the provision of several ESs linked to crop production. Services such as pest, disease and weed control are in fact delivered by mobile organisms that also depend on resources present at a larger scale [11]. Neighbouring non-crop habitats provide alternative food, hosts and winter refuges for a wide range of beneficial organisms [12]. Landscape simplification, with the consequent loss of semi-natural habitats, has been shown to negatively affect the abundance and diversity of pollinator and natural enemy communities [13], potentially compromising the provision of key services that contribute to crop yields [14,15]. Nevertheless, semi-natural habitats can also represent an important source of pests. Complex landscapes might therefore negatively impact crop production because of increased pest colonization (e.g. [16]). Moreover, landscape composition can greatly affect spatial dynamics of crop pathogens and weeds, influencing inoculum and propagule pressure and hence the risks of crop infection and weed invasion [17,18]. Interactions between local management and landscape composition have been principally investigated in relation to one specific service (e.g. pest control [19]) and local soil management has rarely been considered in this context.

Both on-farm and off-farm interventions are therefore expected to affect single ES provision [20]. However, the same driver of change (e.g. farming operations) might affect different ESs in contrasting ways, generating trade-offs when the enhancement of one service takes place at the cost of lessening the provision of another one, or synergies may occur, when multiple ESs are enhanced simultaneously [21]. For example, intensive tillage might increase weed control but at the same time it might cause loss of soil fertility (trade-off). Although the identification of potential trade-offs between multiple services in response to human activities is considered crucial for effective management of agroecosystems [22,23], few attempts have been made to measure these relationships (but see [24]).

The aim of this study was to explore the combined effects of tillage management (conservation versus conventional tillage), fertilization (0 versus 80 kg of nitrogen ha^{-1}) and landscape composition on the provision of and trade-offs between six ESs in winter cereal crops: crop production, disease control, soil fertility, water quality regulation, weed control and pest control (table 1). We hypothesized that (i) conservation tillage would increase the provision of soil fertility and pest control and decrease the provision of disease and weed control, water quality regulation and crop production with respect to conventional management, (ii) fertilization would increase crop production and decrease the provision of disease, weed and pest control and (iii) different soil management processes would affect the potential trade-offs between services. We expected that (iv) complex landscapes would increase the provision of disease, weed and pest control by decreasing the global inoculum pressure, the abundance of weeds in the surroundings and by sustaining more abundant natural enemy communities. We also tested whether landscape composition would moderate the effects of soil management on service provision.

2. Material and methods

(a) Study area, experimental set-up and landscape analyses

The study area was the agricultural landscape of Udine province in northeast Italy (centred on longitude 46°04′00″ N, latitude 13°14′00″ E). This region is an extensive lowland area (approx. 615 km^2) characterized by temperate climate with a mean annual precipitation of approximately 1100 mm and a mean annual temperature of approximately 13°C.

We sampled 15 pairs of neighbouring winter cereal fields (average field size approx. 0.5 ha). Within each pair, one field was managed under conventional tillage and the other under conservation tillage (distance range 0–1.2 km, e.g. electronic supplementary material, figure S1). Field pairs were separated by at least 1 km except for two that were distant by 300 m. Among the 15 pairs, seven were sown with winter wheat and eight with barley in autumn 2013 at an average sowing rate of 200 and 170 kg ha^{-1} (for wheat and barley, respectively). The crop was the same within each pair. Crop rotation for the selected fields was usually a 3-year rotation (maize, winter wheat or barley and soya bean). Conservation tillage included all techniques characterized by non-inversion of soil (e.g. direct drilling, mulch or strip tillage) for at least 5 years (10 years on average, ranging from 5 to 20 years), whereas under conventional tillage the seedbed was prepared by mouldboard ploughing (generally 30–40 cm depth) followed by one or two tills before sowing. Conservation management also included the adoption of cover crops such as Italian ryegrass, vetch, sorghum and common millet, between cash crops.

Field pairs were selected along a gradient of landscape complexity ranging from 1.2 to 22.4% of semi-natural habitats in a 1 km radius around each field, considered a relevant ecological scale for the ESs investigated (e.g. disease control [25], weed control [18], pest control [26]). However, the provision of widely different services can be influenced by different landscape features and it can vary at different scales. We therefore selected and measured two landscape variables at two scales: the proportion of semi-natural habitats (forest patches, hedgerows, tree lines, field margins and grasslands) and the proportion of arable land (annual and perennial crops and intensive meadows; electronic supplementary material, figure S1) at 0.5 and 1 km radii around fields. The proportion of semi-natural habitats was negatively correlated to the proportion of arable land (Spearman's $\rho = -0.53, p = 0.002$). ArcGIS 9.3 was used for landscape analyses of regional land use maps, verified and ameliorated with aerial photograph interpretation and field surveys to increase class discrimination accuracy.

The study was conducted between April and June 2014. In each field, we identified one 20 × 60 m strip located on one side of the field in order to limit interference with farming operations. Within each field pair, the adjoining habitat had similar structure and composition for both fields (i.e. either a grass margin or a hedgerow). Each strip was divided into six 10 × 20 m plots. The two plots located at both ends were considered as buffer zones. Among the four plots left, two non-adjacent plots were fertilized following local farming recommendations (80 kg ha^{-1} of ammonium nitrate in two applications) in March 2014. Within each strip, we replicate the plots twice due to the destructive nature of the measurement of our ecosystem service indicators. No chemical pesticides and herbicides were applied to the plots during the whole crop cycle. The remaining part of the field was fertilized by the farmer according to local recommendations (dose never higher than 100 kg N ha^{-1}).

(b) Ecosystem service indicators

To quantify the provision of the six ESs considered, we selected eight indicators (table 1) following the methodology of Mitchell *et al.* [24]. Some of our indicators were positively related to service provision (e.g. grain yield with the provision of crop production service) whereas others were negatively related (e.g. weed species richness and weed cover with the provision of weed control service). Each indicator was transformed so that higher values corresponded to higher values of service provision (e.g. decreased disease incidence or decreased weed cover equally increased provision of disease and weed control, respectively). The indicators selected are in some cases direct measures of the final service delivered (grain yield for crop production), some represent the ecosystem functions underpinning those ESs (phosphorus saturation for water quality regulation, SOM content for soil fertility, aphid parasitism for pest control), whereas others are general indicators (weed species richness and cover for weed control, predator abundance for pest control). Although the latter are not direct measures of ES provision [27], they are informative proxies for service delivery.

Measurements were performed in different plots as displayed in electronic supplementary material, figure S1, due to the destructive nature of the sampling and at least 3 m from the field border to limit any field edge effects. All service indicators were measured in both fertilized and non-fertilized plots, except for SOM content and phosphorus (P) saturation that were only measured in the fertilized plots because we did not expect any short-term effect of N fertilization on those indicators [28]. For details about indicator measurements, see the electronic supplementary material.

(c) Data analysis

To explore the role of tillage management, fertilization and landscape composition on the service indicators, we used linear mixed-effects models (see model details in table 1). Predator abundance was analysed with generalized mixed-effect models with a Poisson distribution, whereas the other service indicators were analysed with general mixed-effect models (normal distribution). Disease incidence, weed cover and parasitism rate were analysed as non-binomial data and logit-transformed to achieve normal distribution of model residuals [29] because generalized mixed-effect models failed to converge or displayed large overdispersion. In one field, the yield samples were damaged. The analysis regarding grain yield was thus based on data from 29 fields.

The analyses of crop production, disease control, pest control and weed control included tillage, fertilization, landscape and their interactions as fixed effects. Aphid abundance was included as a covariate in the models exploring the effects of the treatments on predator abundance and aphid parasitism rate. The analyses of SOM content (soil fertility) and P saturation (water quality regulation) did not include fertilization because only fertilized plots were sampled. As we quantified two landscape variables at two spatial scales, a total of 32 models were run: the eight indicators were tested against four different landscape variables (the proportion of semi-natural habitat and of arable land at 0.5 and 1 km scales). The model displaying the lowest AICc was considered as the best fitting model. Crop type was initially included in all the models as a further fixed factor to test for potential effects of different crop species on services' provision. As crop species did not influence any response variable ($p > 0.05$), it was removed from the models presented here.

For the analyses of grain yield (crop production), disease incidence (disease control), weed species richness and weed cover (weed control), predator abundance and aphid parasitism rate (pest control), we included field pair and field ID as random factors. The analyses of SOM content (soil fertility) and P saturation (water quality regulation) included only pair ID as a random factor because only fertilized plots were sampled (one value per field).

To evaluate the effects of different soil management on the relationships between ESs, we calculated Spearman's rank correlations between different indicators for each treatment combination (four in total: two levels of tillage intensity by two levels of fertilization, [24]). SOM content and P saturation were included in the analyses only under fertilized conditions. All the analyses were performed using the 'base', 'nlme' and 'lme4' packages [30,31] implemented in R Statistical Software v. 3.1.1 [32].

3. Results

Tillage management affected the provision of several ESs (table 2; electronic supplementary material, table S1). Compared with conventional tillage, conservation tillage generally displayed higher SOM content (figure 1*c*), P saturation (figure 1*d*), weed species richness and cover (figure 1*e* and 1*f*) and predator abundance (figure 1*g*; for details about weed and pest control results, see the electronic supplementary material). Grain yield, disease incidence and aphid parasitism rate showed no difference between the two tillage systems (figure 1*a*, *b* and *h*). Fertilization increased grain yield by 38.5% with respect to non-fertilized plots while it did not affect any other ecosystem service indicators.

Landscape composition influenced the provision of disease and pest control: high proportion of semi-natural areas (1 km) reduced disease incidence and increased predator abundance, whereas high proportion of arable land (1 km) reduced aphid parasitism rate. Moreover, we found landscape composition to differently affect water quality regulation and weed control depending on the tillage system: P saturation decreased with increasing proportion of arable land (1 km) but only in the fields managed under conventional tillage, while under conservation tillage P saturation remained stable along the landscape intensification gradient. Furthermore, the proportion of arable land (0.5 km) increased weed species richness and cover under conventional tillage and decreased them under conservation tillage.

We found soil management to have greatly influenced the relationships between the indicators explored (figure 2; electronic supplementary material, figure S2). Potential trade-offs between ESs were only present under fertilized conditions and more common under conventional tillage: weed control was negatively correlated with soil fertility and partially with pest control (i.e. higher values of weed species richness corresponded to higher levels of SOM and predator abundance). Moreover, water quality regulation was negatively correlated with disease control and pest control: lower values of P saturation corresponded to higher disease incidence and lower aphid parasitism rate. Under conservation tillage trade-offs involved provisioning service: crop production was negatively correlated with pest control (aphid parasitism rate) and disease control. Non-fertilized plots displayed either positive or no relationships between indicators, under both conventional and conservation tillage. Under conventional tillage in fact, pest control (aphid parasitism rate) was positively correlated with weed control. Weed species richness was always positively correlated with weed cover.

4. Discussion

Soil management and landscape composition influenced the provision of multiple ESs in winter cereal crops. Conservation

Table 2. Results of the best fitting linear mixed-effects models (lowest AICc) relating ecosystem service indicators to explanatory variables. To see the results from all the candidate models (four different landscape variables tested), see electronic supplementary material, table S1. Explanatory variables are till (tillage: conservation versus conventional), fert (fertilization: 0 versus 80 kg of N ha^{-1}) and different landscape variables (semi-natural: proportion of semi-natural habitats; arable: proportion of arable land) at 0.5–1 km radius around fields. Models *g* and *h* also included aphid abundance (number of aphids per 50 tillers) as covariate. d.f.; numerator, denominator degrees of freedom. Statistic: *F* for general mixed-effects models (*a,b,c,d,e,f,h*), χ^2 for generalized mixed-effects model (*g*). *p*-Values in italics are statistically significant.

service indicator	d.f.	statistic	*p*-values
(*a*) *grain yield*			
till	1,11	2.76	0.125
fert	1,25	77.10	*<0.0001*
arable (0.5 km)	1,11	1.41	0.260
till × fert	1,25	0.07	0.793
till × arable (0.5 km)	1,11	1.77	0.211
fert × arable (0.5 km)	1,25	3.44	0.075
till × fert × arable (0.5 km)	1,25	0.61	0.442
(*b*) *disease incidence*			
till	1,12	0.05	0.821
fert	1,86	0.31	0.579
semi-natural (1 km)	1,12	6.65	*0.024*
till × fert	1,86	0.01	0.916
till × semi-natural (1 km)	1,12	0.13	0.728
fert × semi-natural (1 km)	1,86	0.55	0.461
till × fert × semi-natural (1 km)	1,86	0.05	0.830
(*c*) *soil organic matter*			
till	1,12	4.76	*0.049*
semi-natural (1 km)	1,12	0.99	0.339
till × semi-natural (1 km)	1,12	1.68	0.219
(*d*) *phosphorus saturation*			
till	1,12	6.39	*0.026*
arable (1 km)	1,12	1.66	0.221
till × arable (1 km)	1,12	13.13	*0.003*
(*e*) *weed species richness*			
till	1,12	14.90	*0.002*
fert	1,26	1.91	0.179
arable (0.5 km)	1,12	0.05	0.832
till × fert	1,26	2.63	0.117
till × arable (0.5 km)	1,12	23.00	*<0.001*
fert × arable (0.5 km)	1,26	0.13	0.720
till × fert × arable (0.5 km)	1,26	0.40	0.530
(*f*) *weed cover*			
till	1,12	10.14	*0.008*
fert	1,26	0.11	0.739
arable (0.5 km)	1,12	0.01	0.924
till × fert	1,26	0.07	0.790

(*Continued*.)

Table 2. (*Continued.*)

service indicator	d.f.	statistic	*p*-values
till × arable (0.5 km)	1,12	10.47	*0.007*
fert × arable (0.5 km)	1,26	0.71	0.408
till × fert × arable (0.5 km)	1,26	2.17	0.153
(*g*) *predator abundance*			
till	1,12	−2.15	*0.031*
fert	1,85	1.14	0.254
semi-natural (1 km)	1,12	1.97	*0.049*
till × fert	1,85	0.87	0.384
till × semi-natural (1 km)	1,12	1.14	0.254
fert × semi-natural (1 km)	1,85	−1.34	0.182
till × fert × semi-natural (1 km)	1,85	−0.79	0.429
(*h*) *aphid parasitism*			
till	1,12	0.23	0.639
fert	1,85	0.71	0.401
arable (1 km)	1,12	6.94	*0.022*
till × fert	1,85	0.76	0.385
till × arable (1 km)	1,12	0.54	0.477
fert × arable (1 km)	1,85	0.58	0.447
till × fert × arable (1 km)	1,85	3.21	0.077

tillage enhanced soil fertility and pest control, decreased weed control and water quality regulation and maintained levels of productivity and crop health comparable to those achieved under conventional management. Fertilization increased crop production but it did not affect the provision of the other ESs considered. Complex landscapes supported higher disease and pest control. We found several interactions between landscape composition and tillage management. The combination of conventional tillage and fertilization resulted in more trade-offs between ESs, while under conservation tillage the number of observed trade-offs was reduced.

(a) Effects of soil management on ecosystem service provision

Tillage affected the provision of soil fertility, pest control, water quality regulation and weed control. The reduced soil disturbance associated with the higher retention of crop residues on the surface of the soil have been widely reported to improve soil structure, soil fertility and general habitat quality for a wide range of organisms [3–9]. Conservation tilled fields displayed higher SOM content compared with conventionally tilled fields. Conservation tillage systems favour the formation of soil aggregates that protect SOM particles from rapid oxidation and, by modifying the edaphic environment, limit SOM degradation [33]. The use of cover crops can provide extended erosion control and greater organic inputs to the soil. We found higher predator abundance under conservation tillage. This confirms previous studies that have shown how arthropod predators are influenced by decreased tillage disturbance [9,34]. For example, spider colonization and establishment have been shown to be favoured under conservation tillage due to the higher soil environment stability and weed density, which promotes a deeper litter and more structurally complex vegetation [4,35]. Aphid parasitism rate showed, instead, no difference between tillage systems. The low aphid occurrence detected in our study may have masked the potential difference in parasitism rate between tillage systems. Reduced tillage intensity was also associated with higher P accumulation in the top soil layer. The retention of crop residues on the surface of the soil can in fact increase the P input, whereas soil acidification caused by nitrogen fertilizers and the general increase in SOM reduce the proportion of available sorption sites for phosphate, increasing the potential for P leaching in the long term [36]. Weed abundance and diversity increased under conservation tillage [3]. Weed community changes under conservation tillage systems, from increased diversity and abundance to a shift in species composition have been reported [4,37]. Contrary to our expectations, we did not find conservation tillage to decrease disease control and crop production. The literature reports contrasting effects of conservation tillage on the provision of both services [5]. However, local soil type, climate and concomitant farming practices (e.g. crop rotation) play a major role in shaping the consequences of adopting non-conventional tillage on disease control and crop productivity, influencing for example water infiltration and soil moisture retention [3–5,38].

As expected, fertilization increased grain yield. Fertilizer application is in fact the most common practice to maximize production in the short-term. We did not find any negative effect on disease, weed and pest control provision, though several studies have shown how nitrogen fertilization can increase weed growth, herbivore performance or plant susceptibility to diseases [7,39]. Nevertheless, our study only considered short-term suspension of fertilizer applications in a limited sample area. In the long term, excessive nitrogen fertilization can lead to negative environmental effects such as nitrogen leakage to ground waters, soil eutrophication and increased greenhouse gas emissions [7]. Larger scale and longer term studies are needed to understand fertilization effects on ES provision.

(b) Effects of landscape composition on ecosystem service provision

As expected, landscape composition influenced the provision of both disease and pest control services: a high proportion of semi-natural areas (at the 1 km scale) reduced disease incidence and increased predator abundance, whereas a high proportion of arable land (1 km) reduced aphid parasitism rate. Disease incidence depends on the abundance of inoculum reservoirs in the surrounding fields, which influences pathogen spread and pressure [17,40]. A high proportion of semi-natural habitats in the landscape probably limited the abundance of inoculum reservoirs (e.g. infected wheat fields) limiting the risks of crop infection. Complex landscapes have also been shown to sustain more abundant predator and parasitoid communities and higher pest control [9,41].

Interestingly, we found that the effects of landscape composition on water quality regulation and weed control provision depended on tillage management. We found contrasting effects of landscape composition on weed control under different tillage systems: with an increasing proportion of arable land (0.5 km) weed species richness and cover

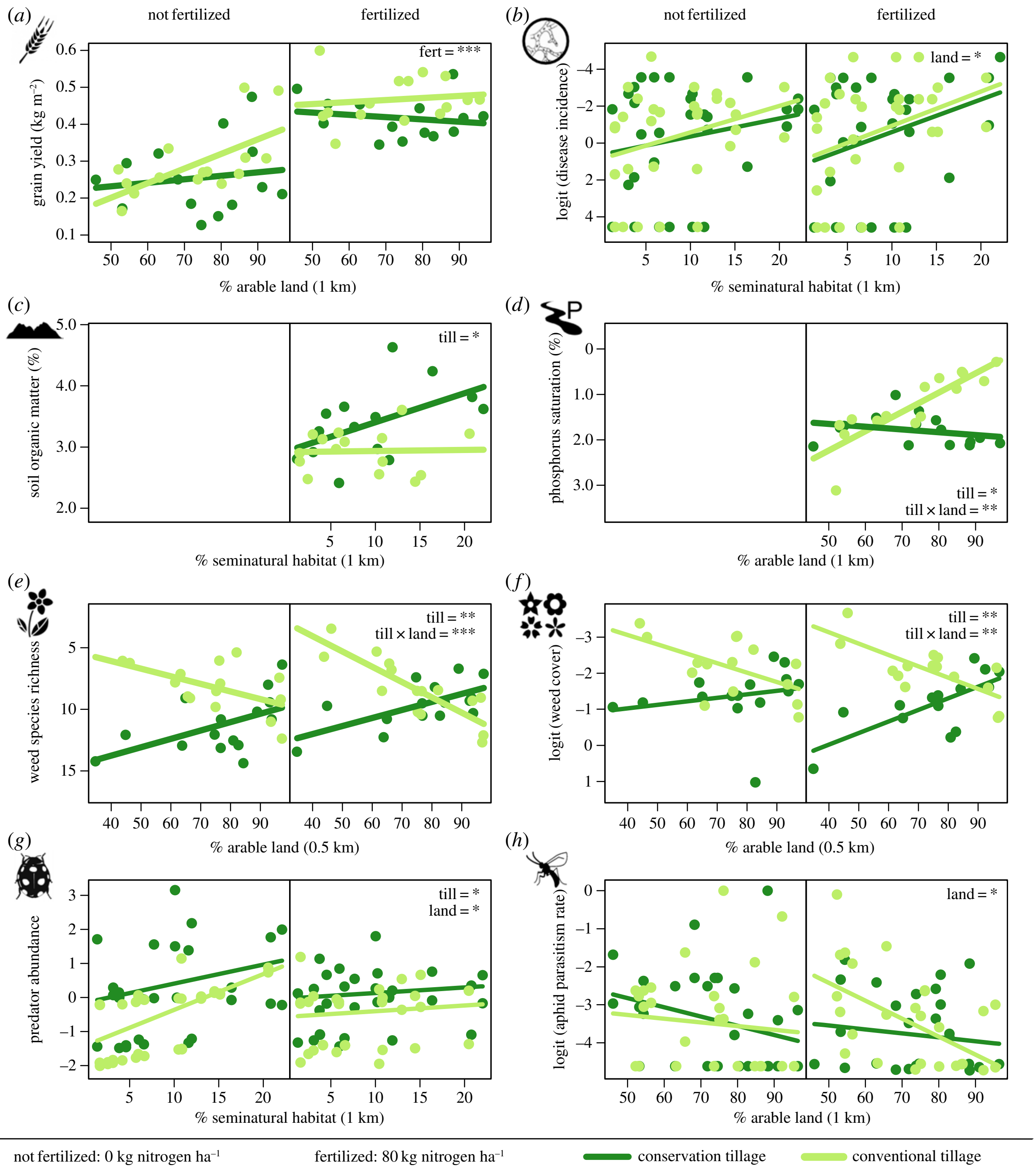

Figure 1. Relationships between ecosystem services and landscape variables for different fertilization treatments (left panels, 0 kg N ha^{-1}; right panels, 80 kg N ha^{-1}) and under different tillage systems (dark green, conservation tillage; light green, conventional tillage). Significant explanatory variables and/or interactions are displayed in bold. *p*-Values are from linear mixed-effects models (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. See table 2). *Y*-axes are reversed for disease incidence, phosphorus saturation, weed species richness and cover (*b,d,e,f*) so that values higher on the axis represent higher levels of ecosystem service provision. Points correspond to partial residuals. (Online version in colour.)

increased in the fields managed under conventional tillage and decreased under conservation tillage conditions. Tillage management is known to create widely different habitat conditions for weed establishment and growth and to shape weed community composition (e.g. [37]). Under conservation tillage, weed communities are richer in perennial species and volunteer crops, being more similar to those inhabiting grasslands, and are therefore more influenced by the immigration of seeds from semi-natural habitats [42]. Conventional tilled fields instead harboured mostly annual weed species typical of more disturbed environments. The presence of arable land in the surrounding areas would hence have a stronger impact on these communities. A high proportion of arable land (1 km) reduced P saturation only in the fields managed under conventional tillage. Straightforward explanations for the influence of landscape composition on such local process might be difficult to find. However, landscapes with different compositions could have different land use histories, whose legacy could affect a variety of services, including water quality regulation (e.g. [43]).

(c) Ecosystem service trade-offs

Soil management greatly influenced the relationships between ESs. Trade-offs only occurred under fertilized conditions and increased with tillage intensity: the most intensive soil management option (fertilization under conventional tillage) scored the highest number of trade-offs while conservation tillage

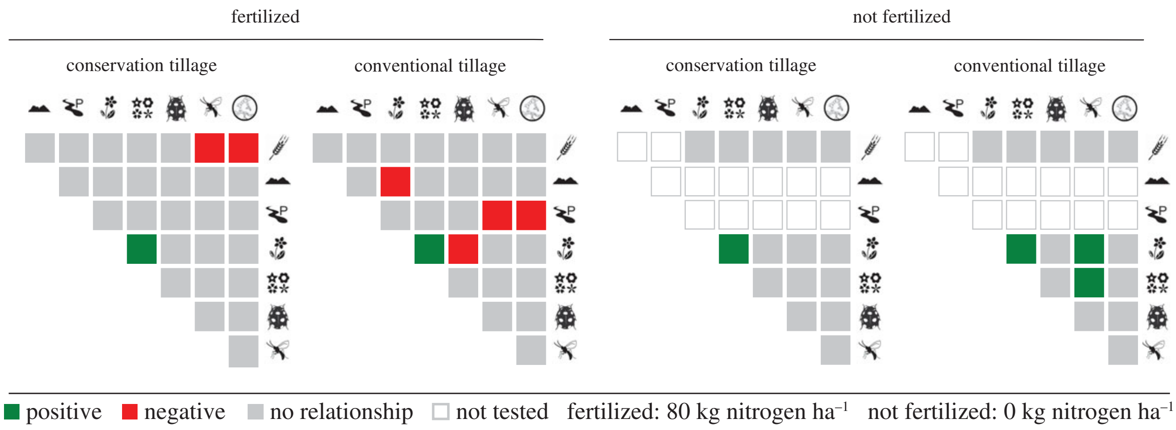

Figure 2. Pairwise relationships between ecosystem services for different fertilization treatments (fertilized: 80 kg N ha^{-1}; not fertilized: 0 kg N ha^{-1}) and under different tillage systems calculated through Spearman's rank correlations. Green are positive and red are negative relationships between ecosystem services (correlation values different, greater or lower than zero, Spearman's rank $p < 0.05$. See electronic supplementary material, figure S2). Grey reflects no correlation whereas empty squares correspond to non-tested relationships (soil organic matter and phosphorus saturation were not measured in non-fertilized plots). Each indicator was transformed so that higher values corresponded to higher values of service provision. The eight ecosystem service indicators are labelled by their respective symbols. (Online version in colour.)

reduced service trade-offs. Nitrogen fertilization and intensive tillage might have accentuated potential negative relationships between ESs through increased crop production and in-field habitat deterioration. The observed trade-offs can be the result of constrasting responses to common drivers or to direct interactions between ESs. However, the observational nature of our study did not allow determination of the mechanistic drivers of final ESs and the trade-offs that may exist in their delivery [27].

Under conventional tillage, weed species richness might depend more on better edaphic conditions (SOM) compared with undisturbed soils dominated by perennial weeds. A more diverse weed community can, in turn, harbour and support a more abundant predator community. Disease control benefited from increased phosphorus availability in the soil (lower water quality regulation, [44]) and this relationship might be stronger when the likelihood of disease incidence increases (higher crop density under fertilized conditions). Moreover, increased plant quality (higher soil phosphorous availability) might indirectly improve parasitoid fitness through improved aphid performance [45]. Conservation tillage, with its increased tendency to accumulate P, may guarantee higher P availability that no longer influences crop quality.

Under conservation tillage, we observed that higher yields came at the cost of lower pest and disease control. A high level of grain yield might correspond to increased crop density, affecting humidity and hence the risk of pathogen proliferation. The surface layer of crop residues under conservation tillage has the potential to increase infection risk [3], possibly strengthening this relationship. Increased crop density could also have reduced the likelihood of parasitoids finding and attacking aphids [46].

(d) Ecosystem service synergies

Synergies were rare. Except for the expected positive association between weed cover and weed species richness, we observed only two positive correlations under unfertilized, conventional tillage conditions: pest control (aphid parasitism) increased together with weed control. These relationships might be the indirect result of the low crop density: the lack of fertilization is likely to increase weed growth through decreased light competition with crop plants [47] and simultaneously to facilitate aphid location for parasitoids. Conservation tillage instead, may support higher weed abundance and diversity that mitigates potential relationships between weed control and crop density and therefore between weed control and parasitism.

(e) Conclusion

Our study provides evidence that soil management and landscape composition influence the provision of multiple ESs in agroecosystems. Common soil management practices such as conventional tillage and inorganic fertilizer applications can result in several trade-offs between ESs, while the adoption of conservation tillage can remove some of these trade-offs. Conservation tillage in agroecosystems may therefore be a successful strategy to support productivity while improving environmental sustainability of farming operations and ecosystem functioning. Nevertheless, the drawbacks of adopting non-inversion tillage need to be faced: specific management practices aiming at reducing P saturation, weed proliferation and the risk of trade-offs between provisioning and other services, are key to realizing the benefits of this tillage system. Beyond local management, complex landscapes sustained the provision of key services to crop production such as disease and pest control. However, interactions between local and landscape processes have to be considered: the adoption of conservation tillage in complex landscapes will benefit from increased pest control but it will suffer from decreased weed control. A deeper understanding of how different management practices shape the provision of multiple ESs and the potential trade-offs between them, may lead to the identification of sound strategies for sustainable management of agroecosystems that limit the trade-offs between crop production and other pivotal ESs.

Data accessibility. Data available from the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.4462q.

Authors' contributions. G.T., S.D.S. and F.B. performed the study. G.T. performed data analysis and led the writing. L.M., S.D.S., F.B. and M.S. participated in data analysis, results interpretation and drafting the manuscript. G.T. and L.M. conceived and designed the study.

Competing interests. We declare we have no competing interests.

Funding. The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no 311781, LIBERATION Project (www.fp7liberation.eu) to L.M.

Acknowledgements. We thank Eliana Francesca Rigato for field assistance. We also thank two anonymous reviewers for the insightful comments that greatly improved the quality of the manuscript. We are grateful to Myron P. Zalucki for comments on an earlier version of the manuscript.

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