Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions.
Sirami et al. PNAS
Supporting Information

SI 1 – Hypotheses on the effects of crop heterogeneity on biodiversity

1.1. Crop compositional heterogeneity (increasing crop diversity)

Hyp 1a. Biodiversity **increases** with increasing crop diversity if different crop types can serve as habitat for different specialized species (single habitat specialization; Andreasen et al. 1991; Weibull et al. 2003). In that case, sampling more crop types will result in observing higher landscape-level biodiversity.

Hyp 1b. Biodiversity **increases** with increasing crop diversity if different crop types provide different resources required for single species (landscape complementation; Dunning et al. 1992), or if specialist species spillover from other crop types in the landscape into the fields sampled (Duelli 1997, Schneider et al. 2016). In that case, for a given number of crop types sampled, landscapes with higher crop diversity will result in observing higher landscape-level biodiversity.

Hyp 1c. Biodiversity **decreases** with crop diversity if most species have high minimum total habitat area requirements, i.e. require large amounts of a single crop type. An increase in the number of crop types available in the landscape results in a decrease in the total area of each crop type available in the landscape, which could hypothetically result in insufficient resources for species associated with individual crop types (Fahrig et al. 2011; Tscharntke et al. 2012).

Hyp 1d. Biodiversity shows a **peaked relationship** with crop diversity available in the landscape (Allouche et al. 2012) if there is an initial increase in biodiversity with increasing crop diversity for reasons explained in Hyp 1a-1b, but at higher levels of crop diversity, each crop type has a lower spatial cover and biodiversity decreases for reasons explained in Hyp 1c.

1.2. Crop configurational heterogeneity (decreasing mean field size)

Hyp 2a. Biodiversity **increases** with decreasing mean field size if landscapes with smaller fields provide easier access to multiple fields for species that require resources occurring in different crop types (landscape complementation).

Hyp 2b. Biodiversity **increases** with decreasing mean field size if landscapes with smaller fields also have higher density of crop edges. This could increase biodiversity measured in sampled crop fields by increasing spillover from adjacent fields or from adjacent semi-natural vegetation occurring between fields.

Hyp 2c. Biodiversity **decreases** with decreasing mean field size if most species show negative edge effects and/or if most species have minimum patch size requirements (separate from their total habitat area requirements, see Hyp1c).

Hyp 2d. Biodiversity shows a **peaked relationship** with decreasing mean field size if there is an initial increase in biodiversity for reasons explained in Hyp 2a-2b and then biodiversity decreases when mean field size reaches minimum patch size requirements for most species (Hyp 2c).

1.3. Interactions between crop compositional and configurational heterogeneity

Hyp 3a. The positive effect of crop diversity on biodiversity is **stronger** when mean field size decreases (and vice-versa) if most species require multiple land cover types easily accessible (landscape complementation). This is because increasing crop diversity increases the chance that all required crop types are available, and decreasing field sizes increases accessibility among the required crop types.

Hyp 3b. The positive effect of crop diversity on biodiversity is **weaker** when mean field size is low if most species require landscape complementation and have minimum patch size requirements. Similarly, the positive effect of decreasing mean field size on biodiversity is **weaker** when crop diversity is high if the presence of a distinct crop type in the adjacent field results in a negative edge effect for most species within the sampled field.

Hyp 3c. The positive effect of crop diversity on biodiversity is **independent** of mean field size if most species are highly mobile and can access multiple fields regardless of mean field size. The positive effect of decreasing mean field size on biodiversity is **independent** of crop diversity if most species in landscapes with low mean field size primarily benefit from an easier access to semi-natural cover, in particular to semi-natural linear elements, rather than to multiple fields.

1.4. Interactions between crop heterogeneity and semi-natural cover

Hyp 4a. The positive effect of **crop diversity** on biodiversity is **stronger** when semi-natural cover (SNC) increases if most species require complementary resources found in semi-natural cover types and several crop types (e.g. species require SNC + crop A + crop B).

Hyp 4b. The positive effect of decreasing **mean field size** on biodiversity is **stronger** when semi-natural cover (SNC) increases if most species in landscapes with low mean field size primarily benefit from an easier access to semi-natural cover, in particular to semi-natural linear elements, rather than an easier access to multiple fields.

Hyp 4c. The positive effects of crop heterogeneity on biodiversity is stronger in landscapes with **intermediate amounts of semi-natural cover** than in landscapes with very low or very high semi-natural cover (Tscharntke et al. 2012). In landscapes with no or very low semi-natural cover, species pool may be small and species may be well adapted to intensive agriculture, and biodiversity may therefore remain unaffected by crop heterogeneity levels. In landscapes with high semi-natural cover, biodiversity levels may be high everywhere due to widespread spill-over effects, and may remain unaffected by crop heterogeneity levels.

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SI 2 – Region and landscape selection

2.1. Region selection

We selected eight agricultural regions (Fig. S2.1) that belong to six different ecoregions (Olson et al; 2001)(51) : Eastern Great Lakes lowland forests (Eastern Ontario in Canada), Celtic broadleaf forests and English lowland beech forests (East Anglia in United Kingdom), Atlantic mixed forests (Armorique, Plaine et Val de Sèvre in France), Western European broadleaf forests (Goettingen in Germany, Coteaux de Gascogne in France), Iberian sclerophyllous and semi-deciduous forests (Lleida in Spain) and Northeastern Spain & Southern France Mediterranean forests (Camargue in France). Topography varied from flat (e.g. Camargue, Eastern Ontario) to intermediate (e.g. Goettingen, Lleida), to hilly (e.g. Coteaux de Gascogne). Climate varied from dry (e.g. Lleida) to humid (e.g. East Anglia). Complexity in crop field shapes varied from rectilinear (e.g. Camargue, Eastern Ontario) to intermediate complexity (e.g. Coteaux de Gascogne, Armorique) to complex field shapes (e.g. Lleida). Specific agricultural products were found in some regions, e.g. dairy (Armorique), olives (Lleida) or rice (Camargue). Diversity of agricultural cover types varied from low (e.g. Camargue, Lleida) to high (e.g. Coteaux de Gascogne, Plaine et Val de Sèvre). Mean field size varied from 1.2 ha in Lleida and 1.4 ha in Armorique to 4.4 ha in Eastern Ontario and 4.7 ha in East Anglia.
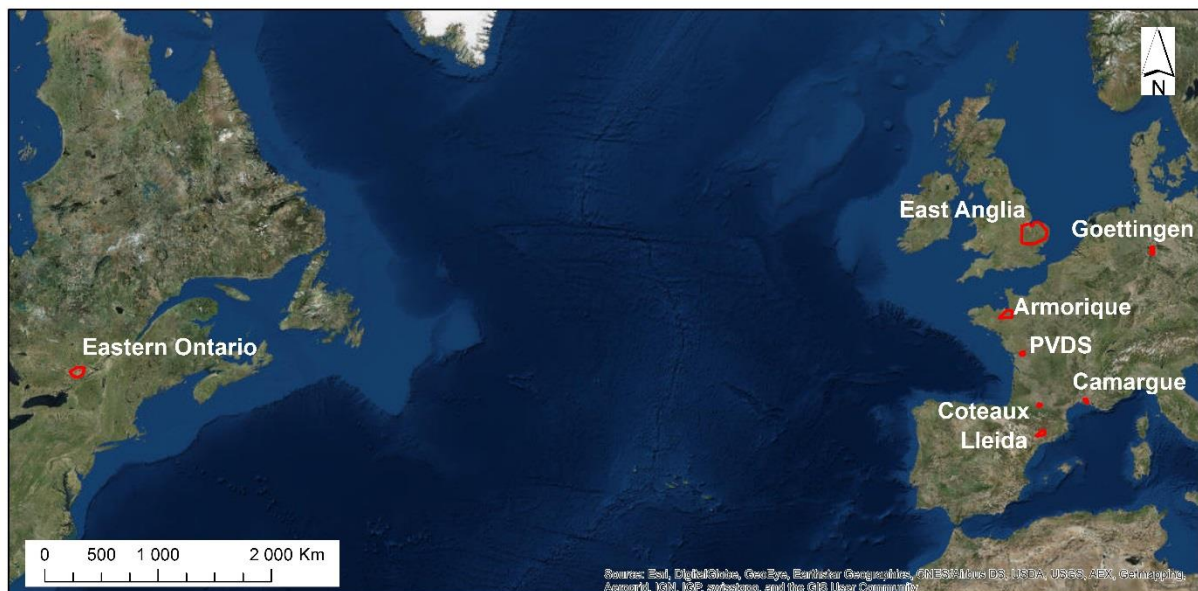

Figure S2.1. Locations of the eight study regions in Europe and North America.

2.2. Landscape selection

The purpose of the landscape selection protocol was to select in each region a set of landscapes in a pseudo-experimental design (also called a "mensurative experiment") which aimed at selecting agricultural landscapes (between 60 and 100% of agricultural cover) along two independent gradients of crop compositional and configurational heterogeneity. The general protocol is detailed in Pasher et al. (2013).

We used the highest resolution and most recent remotely sensed data or the best land cover map available within each region. We delineated all fields (contiguous production cover), even when adjacent fields contain the same agricultural cover type (as they may belong to different farmers or may be managed differently). We attributed each field to one of the following 34 agricultural cover types: cereal, fallow, alfalfa, clover, ryegrass, grassland, rice, corn, sunflower, sorghum, millet, moha, oilseed rape, mustard, pea, bean, soybean, linseed, orchard, almond, olive, vineyard, mixed vegetables, sugar beet, asparagus, carrot, onion, parsnip, potato, tomato, melon, strawberry, raspberry, wild bird cover (i.e. a spring sown crop left unharvested over winter to provide food for farmland birds). We also delineated patches of non-agricultural cover (woodland, open land, wetland and built-area).

We then calculated crop compositional heterogeneity (Shannon diversity index of the crop mosaic) and crop configurational heterogeneity (mean size of agricultural fields) as well as agricultural cover.

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We selected spatially independent agricultural landscapes (between 60 and 100% of agricultural cover) within each region (Fig. S2.2), representing the maximum variation for both crop compositional heterogeneity and crop configurational heterogeneity.
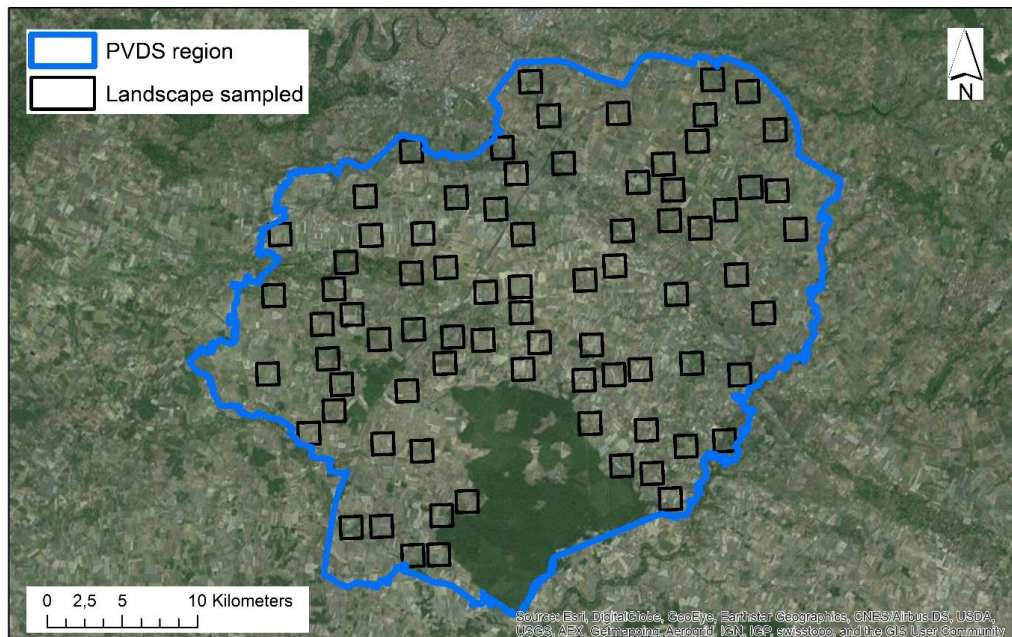

Figure S2.2. Spatial distribution of landscapes sampled in one of the eight regions (PVDS = Plaine et Val de Sèvre).

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SI 3 – Multitrophic diversity sampling

3.1. Sampling site selection

Disentangling the effects of crop diversity and mean field size on multitrophic diversity required sampling many landscapes. Trade-offs between the number of landscapes sampled and the number of sampling sites per landscape were unavoidable. Whereas studies assessing the effect of landscape structure on biodiversity are often based on a single sampling site per landscape, we decided to sample three sampling sites (i.e. three agricultural fields) within each landscape of 1 x 1 km (Fig. S3.1). These sites were located at least 200 m apart from each other, at least 50 m from the border of the 1km x 1km landscape, and at least 50 m from non-agricultural cover such as forests.

We sampled either one, two or three distinct crop types per landscape. We located these sampling sites in dominant crop types within each region. When this was not feasible, we located sampling sites in crop types available within a given landscape while limiting correlations between crop types sampled and the two heterogeneity gradients within each region (see further details in SI 5).

At each sampling site, we selected two parallel 50 m 'transects', one located at the field edge and the other inside the field 25 m away from the first transect (Fig. S3.2).
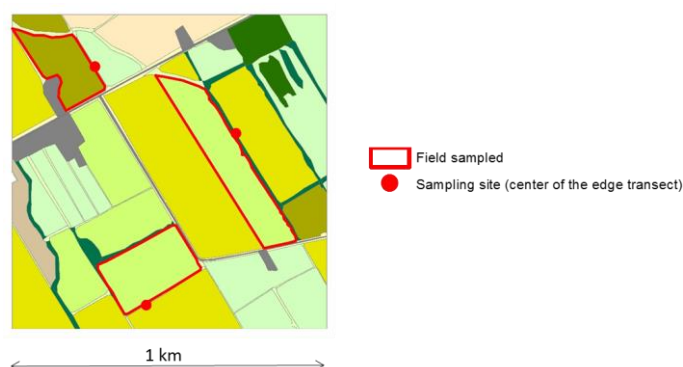

Figure S3.1. Example landscape showing the three selected sampling sites.

3.2. Multitrophic diversity sampling within each sampling site

Multitrophic diversity sampling occurred between 2011 and 2014 depending on the region and landscape (Table S3.1).

Table S3.1. Number of landscapes sampled and main crop types sampled within each region and each year.

Region	2011	2012	2013	2014	Total	Crop types sampled
Armorique			30	10	40	cereal, corn, grassland
Camargue			32	8	40	rice, cereal
Coteaux			20	12	32	cereal, corn, sunflower
East Anglia		30	30		60	cereal, sugar beet, oilseed rape
Goettingen			32	20	52	cereal, oilseed rape, grassland
Lleida			25	15	40	cereal, almond, olive
Eastern Ontario	46	47			93	corn, soybean, grassland
PVDS			48	48	96	cereal, grassland, oilseed rape

All taxa were sampled using sampling methods commonly used in the literature (point counts, traps, visual surveys; Fig. S3.2; Fahrig et al. 2015).
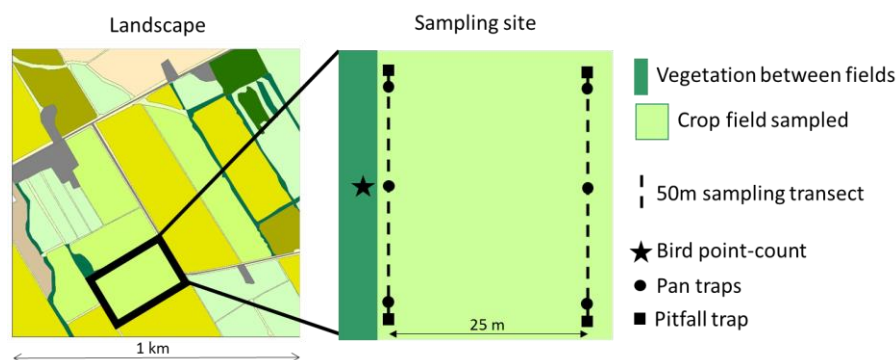
Figure S3.2. Multitrophic diversity sampling design within each sampling site within each landscape (1 km x 1 km).

While trade-offs between the number of sites sampled and sampling intensity at each site were necessary, our sampling efforts (see below: number of traps, length of transects, number of visits) were consistent with the literature (e.g. Pollard and Yates 1993, Bibby et al. 2005, Geiger et al. 2010). Table S3.2 shows the number of species and specimens we sampled for each taxa.

Table S3.2. Number of species and specimens (occurrences for plants) for each taxa.

	Species	Specimens
All taxa	2795	167028
Bees	343	13326
Birds	208	10911
Butterflies	109	10605
Carabids	256	42547
Hoverflies	146	21491
Plants	1229	30276
Spiders	504	37872

Plants - Plant surveys were conducted along the field edge and in the field interior transects. Percentage cover was recorded for each species. Each transect was 1 m wide and 50 m long and represented a total surveyed area of 20 m², except in Eastern Ontario where plant survey transects were 2m wide, represented a total surveyed area of 100 m² and the field edge transect included both the field and the boundary vegetation. Plant surveys were conducted once, except in Eastern Ontario, Goettingen and East Anglia where surveys were conducted twice.

Bees and hoverflies – Bees and hoverflies were sampled using colored pan traps, except for hoverflies in Eastern Ontario which were sampled by sweep-netting along the two transects. Plastic bowls painted in UV blue, white or UV yellow were placed in pairs at each end and at the center of each transect. As a result, we used six pan traps per transect, 12 pan traps per sampling site and 36 pan traps per landscape. The height of pan traps was adjusted to vegetation height. Cups were filled with water, with three drops of odorless soap added per 1L of water. The traps were left in the field for four days. The insects were then stored in 70 % ethanol and later identified to species level. Bee and hoverfly sampling was carried out twice during the growing season (April-July), the dates being selected in each region based on regional climatic conditions. Therefore rarefied species richness could not be calculated. Due to technical and financial constraints, bees could only be identified to species level in seven of the eight regions, and in a total of 183 landscapes. This did not affect our results (see section 3.3 of this SI).

Carabids and spiders - Carabids and spiders were sampled using pitfall traps (Bertrand et al. 2016). Cups were half-filled with a solution of 10 drops of soap and 10 g of salt per 1L of water and placed in the ground. One trap was placed at each end of each transect (two traps per transect and four per sampling site in total). The traps were left in the field for four days. Arthropods were then stored in 70 % ethanol and carabids and adult spiders were later identified to species level. Carabids and spiders were sampled at the same time as the bee and hoverfly sampling (above). They were carried out only once in East Anglia in 2012 due to bad weather conditions and could not be conducted in rice fields in Camargue due to the presence of water.

Butterflies - Butterfly surveys were conducted along the field edge and in the field interior transects (Pollard and Yates 1993). Surveys were conducted on calm (Beaufort scale < 3), sunny days, when the temperature was > 15°C. The observer recorded all butterfly species observed within an imaginary 5 m-sided box (2.5 m to each side, 5 m in front and 5 m high) during approximately 10 min per transect (Pollard and Yates 1993). Individuals that could not be identified by sight were captured with a butterfly net for closer examination (survey time was stopped during capture and identification). Surveys were conducted once, except in Eastern Ontario, Goettingen and Lleida were surveys were conducted twice.

Birds - Birds were surveyed using 10-minutes point counts (Bibby et al. 2005) located at the center of the border transect. All individuals singing or seen within a distance of 100m were recorded. Birds flying across were considered as transients and thus not included. Counts were conducted twice, except in East Anglia in 2012 due to bad weather conditions, in Ontario and in rice fields in Camargue due to the specific phenology of this crop type, where they were conducted once. Surveys were conducted during the peak breeding season, between April and June depending on the region, and during peak activity hours, from 1 to 4 hours after sunrise and under good weather conditions.

Note on detection and rare species – Our sampling scheme presents the following characteristics : 1) the three fields within each landscape often correspond to different crop types and therefore correspond to different species pools; 2) we only sampled each landscape during a single year; 3) we sampled some taxa across two sessions within the sampling season but these sessions target distinct communities (e.g. spring versus summer spider communities); 4) some protocols involve multiple sampling within the field (e.g. several pitfall traps along the edge transect and several pitfall traps along the center transect) but these traps cannot be considered as replicates due to the high level of heterogeneity within fields, both between transects and within a transect. As a result, we do not think we have truly replicated data that would allow us computing species richness estimators such as the Chao estimator. Nevertheless, because we used standard protocols commonly used in the literature, we believe that when pooling the data at the landscape level, our uncorrected data is a good proxy of species richness for each taxa studied.

3.3. Multidiversity
An important challenge when studying the overall effects of crop heterogeneity on multitrophic diversity is that different taxa might respond differently (Flynn et al. 2009; Kormann et al. 2015; Concepción 2016). Indeed, we observed weak correlations among taxa within our dataset (Table S3.3) and significant differences in the response of taxa (Fig. 4 in the main text).

Table S3.3. Mean species richness per landscape ± standard deviation for each taxa and correlations among taxa (Pearson correlation coefficients). * p<0.05; ** p<0.01; *** p<0.001.

	Mean SR	birds	bees	butterflies	carabids	hoverflies	plants
birds	18.7±6.7						
bees	11.2±4.6	0.11					
butterflies	5.4±2.9	0.03	0.14				
carabids	12.3±6.8	0.01	-0.18*	0.13**			
hoverflies	6.4±3.7	-0.04	0.14	0.09	0.25		
plants	44.9±17.5	0.19	-0.07	0.23	-0.21	0.12	
spiders	20.6±11.5	0.17*	0.41***	-0.20**	0.34***	0.16***	-0.27

To test the overall effects of crop heterogeneity on multitrophic diversity, we investigated methods developed by Allan et al. (2014) to study ecosystem multifunctionality. Such approach differs from testing how crop heterogeneity impacts each taxa separately by searching for optimal landscape conditions that promote most taxa simultaneously.

A first approach to achieve this is to calculate a multidiversity index based on the averaged approach (Byrnes et al. 2014). This approach consists simply in calculating the average standardized values of multiple taxonomic diversities for each landscape, where SR_i is the number of species for taxa i in a given landscape, as follows:

$$\text{Average-based Multidiversity} = \frac{1}{7} \times \sum_{i=1}^{n=7} \text{scale}(SR_i, \text{center=T}, \text{scale=T})$$

Although this averaging approach provides an intuitive method to assess changes in diversity across multiple taxa simultaneously (Allan et al. 2014), the averaged-approach includes some biases. For instance, very high averaged-multidiversity values implies that all groups exhibit high diversity. However, intermediate averaged-multidiversity values are difficult to interpret and it is impossible to differentiate situations where (i) diversity values are intermediate for all taxa simultaneously; or (ii) diversity values are very high for some groups while they are very low for others, i.e. trade-offs among taxa (Byrnes et al. 2014).

To overcome this limitation, we used a threshold approach (Zavaleta et al. 2010) not biased by potential trade-offs among taxa (Byrnes et al. 2014). The objective of this approach is to assess the ability of agricultural landscapes to simultaneously host at least a given percentage, or threshold (x), of the maximum species richness observed for each taxa (SRmax). Because SRmax is likely to vary between regions, we chose to use the 95th percentile of the maximum observed species richness within each region as SRmax.region for each taxa. We then calculated the multidiversity index based on the following formula:

$$\text{Threshold} - \text{based Multidiversity (Tx. landscape)} = \frac{1}{7} \sum_{i=1}^{n=7} (\text{SR}\,i > (x \times \text{SRmax. region}\,j))$$

where SR_i is the number of species for taxa i, x is the minimum % to reach and SRmax.region is the maximum species richness for group i in the region the landscape considered belongs to. For a given taxon, if SR_i is above the threshold, this taxon is associated with the value 1. The sum ranges between 0 and 7, and the multidiversity index ranges between 0 and 1.

We calculated this multidiversity index for each threshold x between 20 and 90% (every 10%). For each threshold x, the multidiversity index was smoothed by calculating the average over the interval [x − 10%, x + 10%] (Le Bagousse-Pinguet et al. 2019). It is recommended to focus on intermediate thresholds since care should be taken to avoid over-interpreting high or low thresholds (Lefcheck et al. 2015) and intermediate thresholds have been shown to provide an effective measure of multitrophic diversity in agricultural landscapes (Byrnes et al. 2014). We chose to focus our analyses on the threshold of 60% after checking that the distribution of T60.landscape allows developing robust linear statistics (Fig.S3.3). Nevertheless, we verified that our results were not sensitive to the threshold selected (Fig. S5.2 in SI 5).
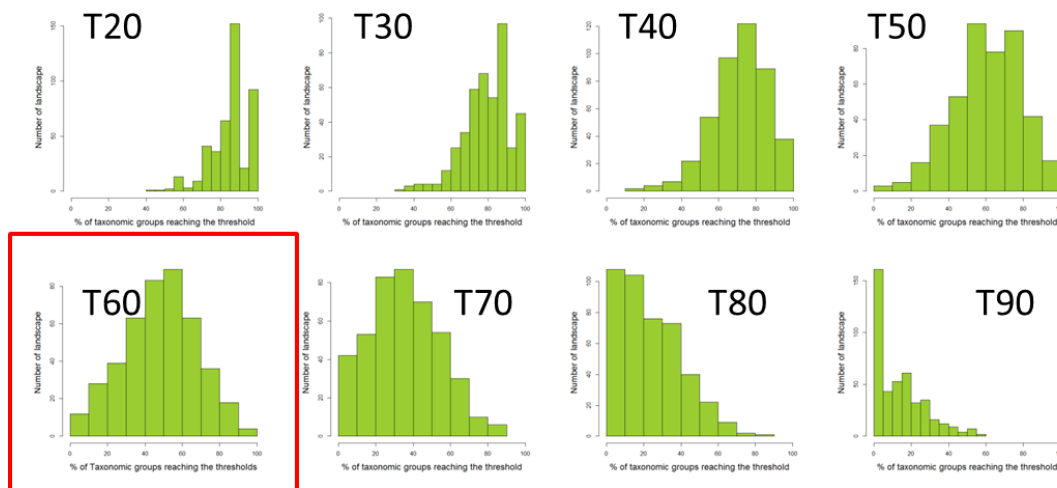

Figure S3.3. Distribution of the threshold-based multitrophic diversity calculated at the landscape level for thresholds between 20 and 90%.

A high multidiversity value based on a threshold of 60% means that most taxa are associated with species richness levels higher than 60% of the regional maximum (SRmax.region) observed in our study. Note that (i) T60.landscape was highly correlated with the averaged multidiversity index in our dataset and other threshold-based multidiversity indices (Table S3.4) (ii) our results were not sensitive to the threshold selected (Fig. S5.1 in SI 5).

Table S3.4. Correlation between average-based multidiversity (M), various threshold-based multidiversity indices calculated at the landscape level (T) and species richness for each taxa. Colors correspond to increasing correlation values (from orange to dark red).

	M	T20	T30	T40	T50	T60	T70	T80	Plant	Bee	Syrphid	Butterfly	Carabid	Spider	Bird
M	1	0.48	0.60	0.71	0.80	0.86	0.88	0.86	0.51	0.59	0.39	0.54	0.56	0.64	0.37
T20	0.48	1	0.92	0.77	0.65	0.58	0.52	0.47	0.08	0.19	0.23	0.21	0.07	0.22	0.61
T30	0.60	0.92	1	0.93	0.79	0.69	0.62	0.56	0.15	0.31	0.23	0.28	0.21	0.31	0.59
T40	0.71	0.77	0.93	1	0.93	0.82	0.74	0.66	0.23	0.45	0.27	0.34	0.33	0.40	0.54
T50	0.80	0.65	0.79	0.93	1	0.94	0.85	0.74	0.32	0.54	0.28	0.39	0.41	0.48	0.50
T60	0.86	0.58	0.69	0.82	0.94	1	0.95	0.84	0.38	0.57	0.28	0.44	0.45	0.54	0.46
T70	0.88	0.52	0.62	0.74	0.85	0.95	1	0.95	0.42	0.54	0.29	0.45	0.46	0.59	0.43
T80	0.86	0.47	0.56	0.66	0.74	0.84	0.95	1	0.42	0.48	0.29	0.43	0.45	0.57	0.44
Plant	0.51	0.08	0.15	0.23	0.32	0.38	0.42	0.42	1	0.04	0.01	0.22	0.21	0.18	0.00
Bee	0.59	0.19	0.31	0.45	0.54	0.57	0.54	0.48	0.04	1	0.25	0.24	0.19	0.30	0.12
Syrphid	0.39	0.23	0.23	0.27	0.28	0.28	0.29	0.29	0.01	0.25	1	0.07	0.06	0.06	-0.06
Butterfly	0.54	0.21	0.28	0.34	0.39	0.44	0.45	0.43	0.22	0.24	0.07	1	0.14	0.20	0.03
Carabid	0.56	0.07	0.21	0.33	0.41	0.45	0.46	0.45	0.21	0.19	0.06	0.14	1	0.34	-0.02
Spider	0.64	0.22	0.31	0.40	0.48	0.54	0.59	0.57	0.18	0.30	0.06	0.20	0.34	1	0.15
Bird	0.37	0.61	0.59	0.54	0.50	0.46	0.43	0.44	0.00	0.12	-0.06	0.03	-0.02	0.15	1

Data for bee species richness were only available for 183 landscapes. To determine whether this affected our results, we also calculated the multidiversity index across six taxa (all groups except bees). As there was no difference in results obtained with six or seven taxa, we here only present results for the multidiversity index calculated across seven taxa within 435 landscapes.

R code for calculating the threshold-based multidiversity index (Tx.landscape), based on SRmax.region (the maximum species richness for group i in the region the landscape considered belongs to)

```
mfthres=function(x,df){
        for(i in 2:ncol(df)){
        for (j in 1:length(Region_list)){
            maximum=quantile(df[df$Region==Region_ list [j],i],0.95,na.rm = TRUE) # SRmax.region
            df[df$Region==Region_ list [j],i]<-df[df$Region==Region_ list [j],i]/maximum*100
         }
        }
df2=df[,-1]
out<-df2>=x
nfun<-rowSums(!is.na(out))
out<-rowSums(out,na.rm = TRUE)
out<-out/nfun*100
return(out)
        }
thres<-seq(from = 10, to = 100, by=10) #defining lowest and highest minimum % to reach and interval
fdf<-sapply(thres,mfthres,MF)
fdf<-as.data.frame(fdf)
colnames(fdf)<-paste("T",thres,sep="")

#Averaging approach to smooth the value for each threshold
for(i in 1:ncol(fdf)){
        idx<-(i-2):(i+2)
        idx<-idx[which(idx%in%(1:ncol(fdf)))]
        fdf[,i]<-rowMeans(fdf[,idx])
        fdf[,i]<-round(fdf[,i])
        }
Threshold<-fdf
```

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SI 4 – Land cover mapping and landscape metrics

4.1. Land cover mapping
Land cover was mapped based on remotely-sensed data and ground-truthing. All cover types, including fields, linear elements between fields and non-agricultural cover types, were mapped as polygons ('patches') (Fig. S4.1). We here refer to 'cover types' rather than 'habitats' because 'habitat' refers to the specific ecological requirements of a given species while 'cover type' refers to a category of land cover without any assumption on species use. This is important in the present study where we assume that many farmland species are likely to use several cover types (landscape complementation).

Agricultural cover types included: cereal, fallow, alfalfa, clover, ryegrass, rice, corn, sunflower, sorghum, millet, moha, oilseed rape, mustard, pea, bean, soybean, linseed, orchard, almond, olive, vineyard, mixed vegetables, sugar beet, asparagus, carrot, onion, parsnip, potato, tomato, melon, strawberry, raspberry, wild bird cover, grassland (including temporary and permanent grassland managed for production purpose) and other crops (unknown or rare crops). We chose to include managed grassland within agricultural cover types because we were interested in assessing the role of spatial heterogeneity within the farmed part of the landscape. We considered grasslands where more than 50% of the biomass was removed as agricultural cover whereas those where less than 50% of the biomass was removed were considered as non-agricultural cover. Linear elements between fields were classified either as woody, grassy, water (e.g. ditches) or tracks. Non-agricultural cover types included woodland (including woody linear elements), open land (e.g. shrubland, grassy linear elements), wetland and built-area (including roads).
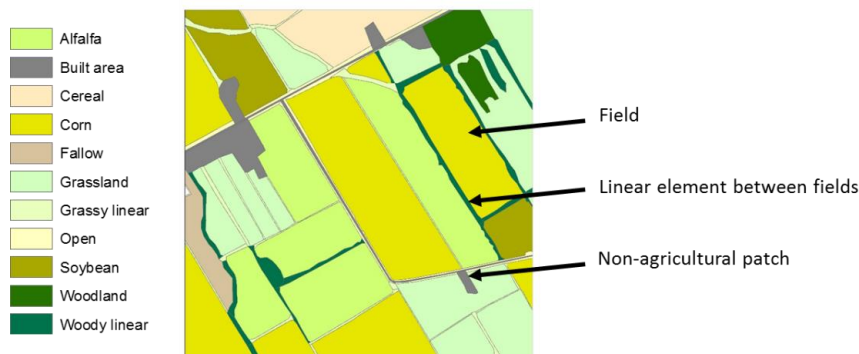

Figure S4.1. Example of land cover map used to calculate variables within each landscape (1km x 1km).

4.2. Landscape metrics
It is well known that different taxa and even species are likely to respond to the landscape structure at different spatial scales. Since our aim was to assess the overall effects of crop diversity and mean field size on a range of contrasted taxa, we chose to calculate landscape variables within a 1x1 km because this spatial extent represent the best compromise between highly mobile taxa (e.g. birds) and taxa with more limited dispersal abilities (e.g. plants or spiders; Kormann et al. 2015).

4.2.1. Number of crop types sampled
The number of crop types sampled ranged from one to three. The diversity of crop types available in the landscape and the number of crop types sampled within each landscape were not heavily correlated (r=0.45).

4.2.2. Crop compositional heterogeneity
We used the diversity of crop types available in the landscape (hereafter 'crop diversity') as a measure of crop compositional heterogeneity. We measured crop diversity using the Shannon diversity index, a widely used metric of landscape heterogeneity (e.g. Bertrand et al. 2016; Bosem Baillod et al. 2017): $H' = -\sum_{i=1}^{n} p_i \ln p_i$ where p_i is the proportion of crop type i in the agricultural mosaic. Note that this metric assumes that all agricultural cover types (defined in 4.1) are considered equally different. This variable does not take into account within-field crop heterogeneity, e.g. intercropping patterns.

The diversity of crop types available in the landscape and the number of crop types sampled within each landscape were not heavily correlated (r=0.45).

4.2.3. Crop configurational heterogeneity

We used mean field size (ha) as a measure of crop compositional heterogeneity. We chose this metric over total field perimeter length per landscape (e.g. Bosem Baillod et al. 2017) because it is directly related to our hypotheses (see SI 1). Moreover it is easier to base practical recommendations for future agricultural policies on mean field size rather than on total field perimeter length. Fields were only mapped within the 1 km² landscape. As a result, for fields located partly outside of the 1 km² landscape, only their area contained within the landscape was considered in calculating mean field size. This may lead to a slight underestimation of mean field size.

4.2.4. Semi-natural cover proportion

We calculated the sum of woodland (including woody linear elements), open land (e.g. shrubland, grassy margins) and wetland cover (including ponds, rivers, ditches) in the landscape.

4.2.5. Total length of semi-natural linear elements

We assessed the total length of vegetation occurring in semi-natural linear elements between fields (SNL, in meters) by calculating half the sum of all semi-natural linear elements located between two fields (e.g. hedgerows, grassy margins). Note that semi-natural linear elements located along roads or urban areas were not included in the calculation of SNL. SNL and mean field size were highly correlated (see Table S5.5. in SI 5).

4.2.6. Latitude and longitude

We calculated the latitude and longitude of the center of each landscape using the WGS 1984 World Mercator projection system.

4.3. Descriptive statistics for the 435 landscapes selected

The 435 landscapes selected across eight regions of Europe and North America had the following characteristics (mean ± sd; see also Table S4.1): 1.94±0.56 crop types sampled, 81.3±9.6 % of agricultural cover, 12.7±8.9 % of semi-natural cover, 5631±3822 m of linear semi-natural elements between fields, mean field size 2.99±2.02 ha and a Shannon diversity index of agricultural cover types of 1.03±0.39 (Fig S4.3). These gradients are representative of most Western European agricultural landscapes (Herzog et al. 2006) and most American agricultural landscapes (Yan & Roy 2016).

Table S4.1. Descriptive statistics for each landscape variable (mean, median, 25th and 75th quartiles, min and max): number of crop types sampled (Crop nb), diversity of crop types available in the landscape (Crop diversity), mean field size (ha), the percentage of semi-natural cover types (SNC), and the length of semi-natural linear elements (SNL).

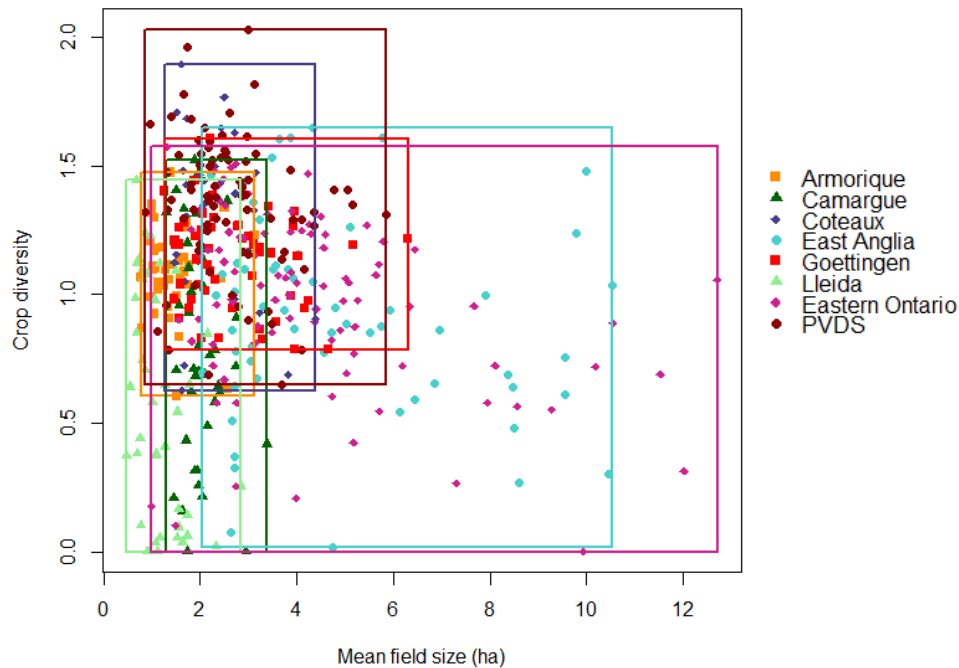|	Crop nb	Crop diversity	Mean field size (ha)	SNC (%)	SNL (m)
Min	1	0.0	0.48	0.0	0
1st quartile	2	0.8	1.71	6.0	3108
Median	2	1.09	2.43	10.9	4824
Mean	1.94	1.03	2.99	12.7	5632
3rd quartile	3	1.31	3.69	17.6	7370
Max	3	2.03	12.71	49.5	27989

Figure S4.3. Variation in crop diversity and mean field size (ha) across the eight regions. Points correspond to selected landscapes (N= 435) and boxes corresponds to the range of crop diversity and mean field size sampled within each region (orange=Armorique, dark green=Camargue, dark blue=Coteaux, light blue=East Anglia, light red=Goettingen, light green=Lleida, pink=Eastern Ontario, dark red=PVDS).

4.4. Effects of the number of crop types sampled vs. the diversity of crop types in the landscape

Biodiversity may increase with increasing crop diversity if different crop types can serve as habitat for different specialized species (single habitat specialization; Fig. S4.4). In that case, sampling more crop types will result in higher observed landscape-level multitrophic diversity. Biodiversity may also increase with crop diversity if different crop types provide different resources required for single species (landscape complementation). In that case, sampling the same number of crop types in landscapes with higher crop diversity will result in higher landscape-level multitrophic diversity.
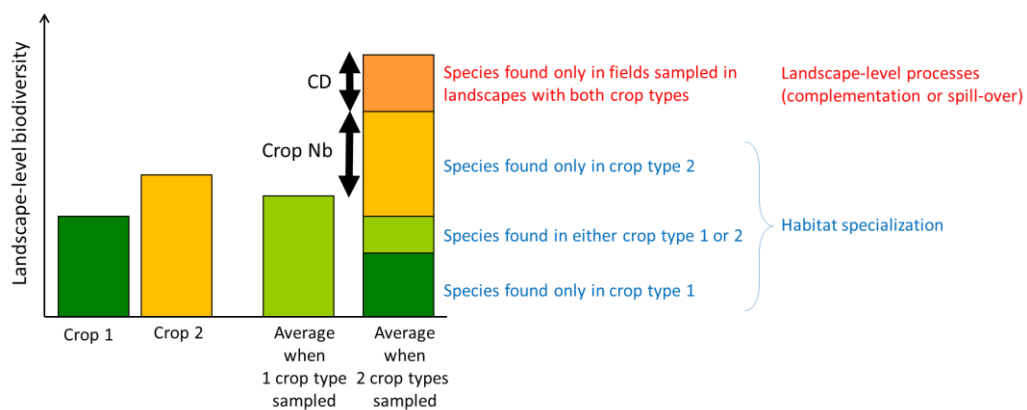

Figure S4.4. Roles of habitat specialization, landscape complementation or spill-over in the potential positive effect of crop diversity on multitrophic diversity (see SI 1). Black arrows represent the effect of our two explanatory variables (CD = increasing the diversity of crop types in the landscape; Crop Nb = increasing the number of crop types sampled).

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Since the diversity of crop types available in the landscape and the number of crop types sampled within each landscape were not heavily correlated (r=0.45), we were able to disentangle the role of these two mechanisms (Fig. S4.5).
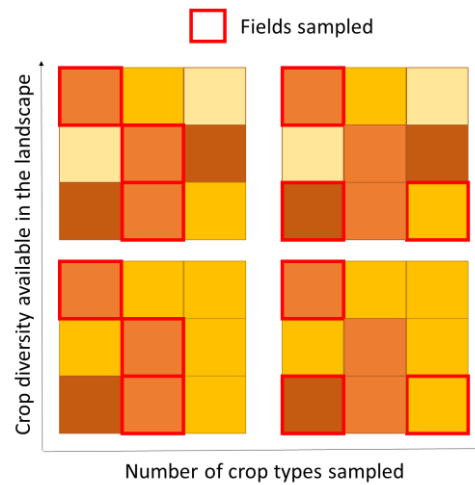

Figure S4.5. Representation of our sampling design allowing us to take into account the potential contribution of habitat specialization and landscape complementation/spillover to the positive effect of crop diversity on multitrophic diversity.

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SI 5 – Complementary analyses

5.1. Details of the model selection and model averaging for multitrophic diversity

We first tested the effect of crop heterogeneity on multitrophic diversity (Model 1).

Model 1: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + (1| Region/Year))

The model selection approach based on ΔAICc<2 resulted in the selection of 10 sub-models (Table S5.1). Using a ΔAICc of 7 did not change the results of the model averaging or results on variable importance. All models included crop diversity (CD), mean field size (MFS), semi-natural cover (SNC), the number of crops sampled per landscape (Crop nb) and the interaction between crop diversity and semi-natural cover (CD x SNC). The AICc of the Null model was 3709 while the AICc of the best model was 3667, i.e. a ΔAICc of 42, suggesting that the best selected models were far more parsimonious than the null model including only Region and Year as random effects.

Table S5.1. List of all sub-models selected and used for the model averaging approach for model 1.

Sub-model	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9	1-10	Null
Lat											
Lon											
CD											
CD²											
MFS											
MFS²											
SNC											
Crop nb.											
CD x SNC											
MFS x SNC											
CD xMFS x SNC											
Marginal R²	0.13	0.13	0.12	0.15	0.15	0.12	0.14	0.12	0.14	0.13	0
Conditonal R²	0.36	0.37	0.35	0.38	0.38	0.36	0.37	0.37	0.37	0.36	0.23
df	10	11	9	11	12	10	10	11	11	11	–
AICc	3667.5	3668.09	3668.16	3668.21	3668.75	3668.75	3668.86	3669.36	3669.39	3669.56	3709.7
delta	0	0.59	0.66	0.7	1.24	1.24	1.35	1.85	1.89	2.05	42.23
weight	0.17	0.13	0.12	0.12	0.09	0.09	0.09	0.07	0.07	0.06	–

5.2. Influence of selected threshold on parameter estimates for multitrophic diversity

To test whether the choice of threshold for computing the multitrophic diversity index impacted our conclusions, we ran model 1 for all thresholds from T20 to T80 (i.e. proportion of taxa for which the species richness is equal to or higher than 20% to 80% of the regional maximum species richness per landscape).

Parameters estimates were consistent across the range of thresholds (Fig. S5.1). Moreover, variations in parameter estimates suggests that increasing mean field size may be particularly effective to reach intermediate multidiversity thresholds (i.e. between 30 and 50% of regional maximum) whether increasing semi natural cover may be effective to reach higher multidiversity threshold (i.e. above 50% of regional maximum).

This comparison confirms the validity of choosing T60.landscape, i.e. the proportion of taxa for which the species richness is equal or higher than 60% of the regional maximum species richness per landscape.
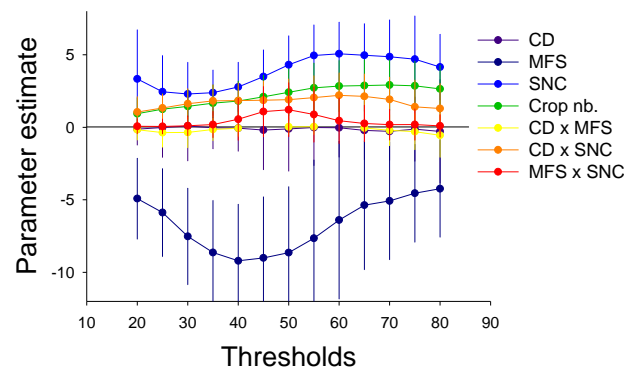

Figure S5.1. Parameter estimates based on model 1 for different thresholds. Thresholds correspond to the % of SR max used to calculate the multidiversity index. In this paper, we present model outcomes for a threshold of 60%, i.e. we use the proportion of taxa that exceeded 60% of the maximum species richness.

5.3. Variation in the response of multitrophic diversity among regions

To test whether the effects of crop diversity, mean field size and semi-natural cover on multitrophic diversity measured at the landscape level (T60.landscape) varied significantly among regions we added random effects for region on the slopes of crop diversity, mean field size, semi-natural cover as well as the interaction between crop diversity and semi-natural cover (model 2). We assumed that the effects of region on the intercept and slopes were uncorrelated. To test whether Region had a significant effect on the slope of either crop diversity, mean field size, semi-natural cover as well as the interaction between crop diversity and semi-natural cover, we used the function exactRLRT from package RLRsim.

*Model 2: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + (1|Region/Year) + (0+CD|Region)) + (0+MFS|Region) + (0+SNC|Region) + (0+CD:SNC|Region))*

Table S5.2. Comparison of model 1 and model 2 (i.e. model including a random effect of region on slope). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 1	model 2
Crop diversity (CD)	-0.03 [-2.07 ; 2.01]	-0.16 [-2.22 ; 1.9]
Mean field size (MFS)	-6.39 [-11.85 ; -0.94] *	-5.22 [-11.29 ; 0.85] °
Semi-Natural Cover (SNC)	5.07 [2.87 ; 7.26] ***	4.35 [0.79 ; 7.91] *
Nb of Crops sampled	2.84 [1.07 ; 4.62] ***	3.05 [1.29 ; 4.8] ***
Latitude	1.5 [-3.55 ; 6.55]	
Longitude	3.73 [2.47 ; 9.93]	-2.39 [-8.39 ; 3.62]
MFS²	3.78 [-0.67 ; 8.23] °	3.78 [-2.26 ; 9.83]
SNC²		-2.39 [-8.39 ; 3.62]
CD :SNC	2.20 [0.64 ; 3.76] **	2.06 [0.29 ; 3.82] *
MFS :SNC	1.15 [-0.66 ; 2.96]	1.51 [-0.44 ; 3.46]

The random effect of region on the slope of MFS was significant in model 2 (RLRT = 3.28, p=0.02) whereas the effects on CD (RLRT=0, p=1), SNC (RLRT=0.04, p=0.33) and CD:SNC (RLRT=0.19, p=0.24) were not (Fig. 4). This result confirms that the regional context can modulate the effect of mean field size on multitrophic diversity, but that the positive effects of increasing CD, when SNC is high enough, and decreasing MFS remain valid across all regions (Table S5.2).

5.4. Results on the species richness of taxonomic groups

We tested the effects of crop heterogeneity on the species richness of taxonomic groups (Model 3). To do this, we fitted a model similar to Model 1, using the landscape-level species richness of taxonomic groups (SR) as the response variable. To reflect that species pools vary between taxa, we added Taxon as a random effect.

*Model 3: lmer (SR ~ CD*MFS*SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + (1|Region/Year) + (1|Taxon))*

The effects of crop heterogeneity on the species richness of taxonomic groups were similar to their effects on multitrophic diversity (Fig. S5.2).
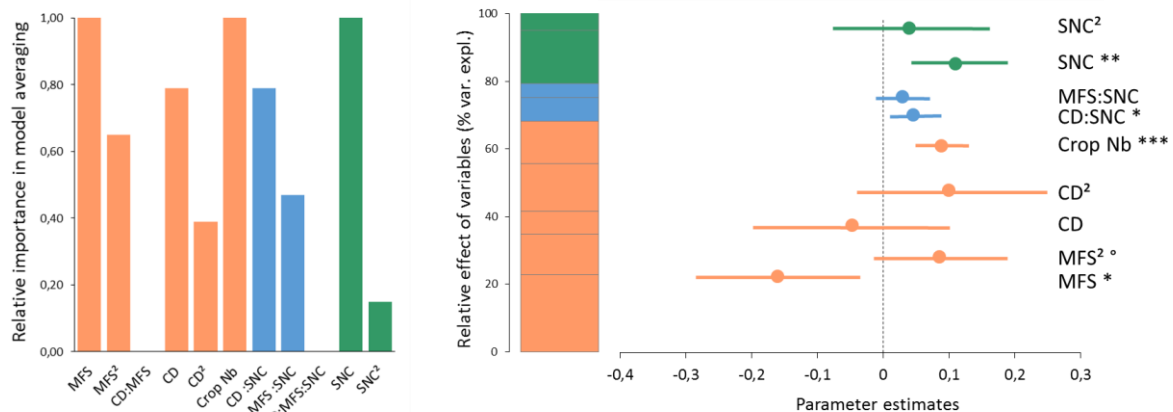
Figure S5.2. Response of the species richness of taxonomic groups to the diversity of crop types available within the landscape (CD), the number of crops sampled (Crop Nb), mean field size (MFS), semi-natural cover (SNC), and interaction terms (CD:SNC, MFS:SNC, see further details in Methods), based on data collected in 435 landscapes located in eight agricultural regions. Covariates (Lon, Lat) were excluded from the figure for simplicity. Importance of each variable in the model averaging approach (model 3) was estimated as the proportion of models where the variable was selected. The relative effect of each variable corresponds to the ratio between its parameter estimate and the sum of all parameter estimates (i.e. the % of variance explained). Parameter estimates and confidence intervals were obtained from a model averaging approach applied to model 3 (Methods). ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001. Variables are grouped in three components: orange = crop heterogeneity (MFS, MFS², CD, CD², MFS:CD, Crop Nb), green = semi-natural cover (SNC, SNC²), blue = interactive effects between crop heterogeneity and semi-natural cover (CD:SNC, MFS:SNC, CD:MFS:SNC).

To test whether the effects of crop diversity, mean field size and semi-natural cover on the species richness of taxonomic groups varied significantly among taxa we added random effects for Taxon on the slopes of crop diversity, mean field size, semi-natural cover as well as the interaction between crop diversity and semi-natural cover (model 4). We assumed that the effects of Taxon on the intercept and slopes were uncorrelated. To test whether Taxon had a significant effect on the slope of either crop diversity, mean field size, semi-natural cover or the interaction between crop diversity and semi-natural cover, we used the function exactRLRT from package RLRsim.

*Model 4: lmer (SR ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + (1|Taxon) + (1|Region/Year) + (0+CD| Taxon)) + (0+MFS| Taxon) + (0+SNC| Taxon) + (0+CD:SNC| Taxon))*

Table S5.3. Comparison of model 3 and model 4 (i.e. model including a random effect of taxa on slopes). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 3	model 4
Crop diversity (CD)	-0.05 [-0.2 ; 0.11]	-0.05 [-0.21 ; 0.1]
Mean field size (MFS)	-0.16 [-0.28 ; -0.04] *	-0.14 [-0.26 ; -0.03] *
Semi-Natural Cover (SNC)	0.11 [0.04 ; 0.18] **	0.11 [0.06 ; 0.17] ***
Nb of Crops sampled	0.09 [0.05 ; 0.13] ***	0.09 [0.05 ; 0.13] ***
Latitude	0.07 [-0.03 ; 0.16]	0.06 [-0.03 ; 0.16]
CD²	0.1 [-0.04 ; 0.24]	0.08 [-0.07 ; 0.23]
MFS²	0.08 [-0.02 ; 0.19] °	0.07 [-0.03 ; 0.17]
SNC²	0.04 [-0.08 ; 0.16]	0.01 [-0.11 ; 0.13]
CD :SNC	0.04 [0.01 ; 0.08] *	0.05 [0.002 ; 0.09] *
MFS :SNC	0.03 [-0.01 ; 0.07]	0.03 [-0.01 ; 0.07]

The random effect of taxa on the slope of CD (RLRT = 1.94, p=0.06), MFS (RLRT=0.05, p=0.34), SNC (RLRT=0.26, p=0.24) and CD:SNC (RLRT=0.35, p=0.22) were not significant in model 4 (Fig. 5). This result confirms that the effects of crop heterogeneity on species diversity vary only marginally among taxa, and that the positive effects of decreasing mean field size, increasing the number of crop sampled, increasing semi-natural cover, and when semi-natural cover is high, increasing crop diversity, remain valid across all taxa (Table S5.3).

5.5. Correlations and alternative mechanisms at the landscape level

Crop diversity and mean field size are likely to be correlated with several variables, including the overall composition of the crop mosaic, the proportion of grassland in the mosaic or the length of semi-natural vegetation occurring between fields. Disentangling the role of crop heterogeneity from the effects of these other variables is necessary in order to infer potential mechanisms explaining the positive effect of crop heterogeneity on multitrophic diversity. In the present study, some of these additional variables were correlated among themselves, or with our variables of interest. Exploring their role sometimes required running models using a data subset for which relevant variables were uncorrelated. As a result, we could not include all these variables in a single model and present these analyses as separate, complementary analyses.

5.5.1. Role of the identity of crops in the agricultural mosaic

The identity of crop types in the mosaic may vary along the gradients of crop diversity and mean field size. For instance, landscapes with small fields may be composed of more biodiversity-friendly crops. Such a correlation would represent a potential bias in our study and hamper our ability to test the effects of crop heterogeneity on multitrophic diversity.

We investigated the correlation between each crop heterogeneity gradient and the identity of crop types in the mosaic for 435 landscapes from 8 regions. We conducted a Principal Components Analysis on the matrix of percentage cover per agricultural cover type per landscape. The first axis represented 40% of the variance, while the second axis represented 19% of the variance.

The Pearson correlations between crop diversity and the first two axes of the PCA were weak (axis 1: r=-0.03, p=0.56 and axis 2: r=-0.19, p<0.001), as were the Pearson correlations between mean field size and the first two axes of the PCA (axis 1: r=0.21, p<0.001 and axis 2: r=-0.12, p=0.01; Fig. S5.3).
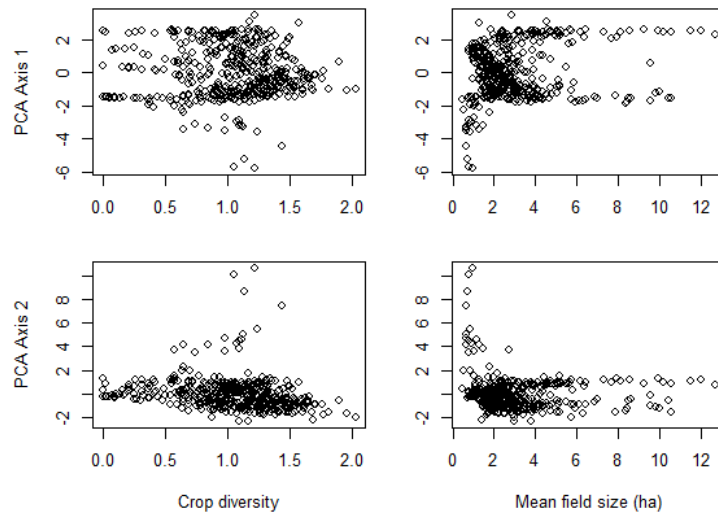

Figure S5.3. Relationships between the two crop heterogeneity gradients and the identity of crop types in the mosaic (axes 1 and 2 of the Principal Components Analysis).

We added the scores of landscapes along axes 1 and 2 of the PCA to model 1 and compared the outcomes of the obtained model (model 5) with those of model 1.

*Model 1: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + (1| Region/Year))*
*Model 5: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + Axis1 + Axis 2 + (1| Region/Year))*

The average model selected based on model 5 included the same variables as the average model selected based on model 1, plus variable PCA Axis 1. Parameter estimates and significance for variables of interest remained unchanged (Table S5.4). This result suggests that the effects of CD, in combination with SNC, and MFS cannot be explained by the composition of crop types occurring in the mosaic.

Table S5.4. Comparison of estimates for model 1 and model 5 – mosaic crop composition (i.e. model taking into account the composition of crop types in the mosaic). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 1	model 5 – mosaic crop composition
Crop diversity (CD)	-0.03 [-2.07 ; 2.01]	-0.06 [-2.1 ; 1.96]
Mean field size (MFS)	-6.39 [-11.85 ; -0.94] *	-6.44 [-11.88 ; -1.01] *
Semi-Natural Cover (SNC)	5.07 [2.87 ; 7.26] ***	5.07 [2.88 ; 7.27 ***
Nb of Crops sampled	2.84 [1.07 ; 4.62] ***	2.84 [1.06 ; 4.62] **
Latitude	1.5 [-3.55 ; 6.55]	1.5 [-3.55 ; 6.55]
Longitude	3.73 [2.47 ; 9.93]	3.73 [-2.47 ; 9.93]
MFS²	3.78 [-0.67 ; 8.23] °	3.73 [-0.72 ; 8.19]
CD :SNC	2.20 [0.64 ; 3.76] **	2.21 [0.65 ; 3.77] **
MFS :SNC	1.15 [-0.66 ; 2.96]	1.15 [-0.66 : 2.96]
PCA axis 1		1.5 [-3.55 ; 6.55]

5.5.2. Role of the proportion of grassland in the crop mosaic

The identity of some ecologically important crop types in the mosaic may vary along the gradients of crop diversity and mean field size. In this study, we chose to include managed grassland within agricultural cover types because we were interested in assessing the role of spatial heterogeneity within the farmed part of the landscape. In our dataset, grassland cover was only moderately correlated with crop diversity (r=-0.001, p=0.97) and mean field size (r=-0.21, p<0.001). However, we were aware that the proportion of grassland in the crop mosaic, in particular permanent grassland, may have a strong positive effect on biodiversity (Öckinger & Smith 2007).

We added the proportion of grassland to model 1 (using data collected in 435 landscapes from 8 regions) and compared the outcomes of the following model (model 6) with those of model 1.

*Model 6: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + Grassland + (1| Region/Year))*

Model selection based on model 6 included the same variables as for model 1, plus Grassland, which had a marginally significant positive effect. However, parameter estimates and significance for other variables of interest remained unchanged (Table S5.5). This result suggests that the effects of CD, in combination with SNC, and MFS cannot be explained by the proportion of grassland in the mosaic.

Table S5.5. Comparison of model 1 and model 6 – grassland (i.e. complete model taking into account the proportion of grassland in the mosaic). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 1	model 6 – grassland
Crop diversity (CD)	-0.03 [-2.07 ; 2.01]	0.18 [-1.9 ; 2.26]
Mean field size (MFS)	-6.39 [-11.85 ; -0.94] *	-6.2 [-11.83 ; -0.59] *
Semi-Natural Cover (SNC)	5.07 [2.87 ; 7.26] ***	5.07 [2.88 ; 7.27] ***
Nb of Crops sampled	2.84 [1.07 ; 4.62] ***	2.73 [0.94 ; 4.52] **
Latitude	1.5 [-3.55 ; 6.55]	
Longitude	3.73 [2.47 ; 9.93]	4.07 [-2.34 ; 10.47]
MFS²	3.78 [-0.67 ; 8.23] °	3.98 [-0.48 ; 8.44] °
CD :SNC	2.20 [0.64 ; 3.76] **	2.25 [0.69 ; 3.81] **
MFS :SNC	1.15 [-0.66 ; 2.96]	1.33 [-0.51 : 3.16]
Grassland		1.87 [-0.26 ; 4.00] °

5.5.3. Role of semi-natural vegetation occurring between fields

Mean field size (MFS in ha) and the length of semi-natural linear elements between fields (SNL) or the length of hedgerows (H) were strongly correlated, particularly in some regions (e.g. Armorique, Table S5.6). As a result, we could not include both MFS and SNL (or MFS and H) in our models and disentangle their effects on multitrophic diversity.

Table S5.6. Pearson correlation coefficients among explanatory variables across and within regions. CD = crop diversity, MFS = mean field size, SNC= proportion of semi-natural cover, SNL= length of semi-natural linear elements between fields, H = length of hedgerows between fields. N = number of landscapes. Correlations between H and CD or SNC were low and are not shown here for simplicity.

	CD-MFS	CD-SNC	CD-SNL	MFS-SNC	MFS-SNL	MFS-H	SNC-SNL	N
All regions	-0.13	-0.27	-0.30	-0.02	-0.44	-0.37	0.13	435
Armorique	-0.03	0.09	0.10	-0.01	-0.71	-0.67	-0.06	40
Camargue	-0.20	-0.25	0.11	-0.06	-0.55	-0.17	-0.59	40
Coteaux	-0.27	-0.22	0.51	-0.31	-0.57	-0.50	-0.24	32
East Anglia	-0.18	0.21	0.18	-0.16	-0.34	-0.23	-0.41	60
Goettingen	-0.17	0.15	0.05	0.15	-0.43	-0.10	-0.10	52
Lleida	-0.40	-0.14	0.16	-0.15	-0.50	-0.23	-0.20	40
Eastern Ontario	-0.34	-0.13	0.27	-0.40	-0.53	-0.43	-0.08	93
PVDS	-0.16	-0.08	-0.02	-0.37	-0.51	-0.57	0.29	78

To test whether our results for MFS were likely due to the correlation with SNL or H, we selected a subset of landscapes for which explanatory variables, in particular MFS and SNL as well as MFS and H, were uncorrelated

i.e. with a Pearson correlation coefficient <0.56 for each pair of explanatory variables, within each region (Table S5.7).

Table S5.7. Pearson correlation coefficients among explanatory variables, across and within regions, within the subset of landscapes (274 landscapes) used to test for the influence of SNL and H on our results for the effects of crop heterogeneity. CD = crop diversity, MFS = mean field size, SNC= proportion of semi-natural cover, SNL= length of semi-natural linear elements between fields, H = length of hedgerows between fields. N = number of landscapes.

	CD-MFS	CD-SNC	CD-SNL	MFS-SNC	MFS-SNL	MFS-H	SNC-SNL	N
All regions	-0.15	-0.30	-0.40	-0.08	-0.27	-0.28	0.30	274
Armorique	-0.02	0.29	0.40	-0.06	-0.04	-0.15	-0.33	20
Camargue	-0.25	-0.19	-0.14	-0.56	-0.05	-0.15	-0.09	20
Coteaux	0.31	-0.38	0.20	-0.46	0.06	-0.12	-0.52	20
East Anglia	-0.15	-0.04	0.35	-0.32	-0.18	-0.31	-0.40	43
Goettingen	-0.26	0.10	0.10	-0.02	-0.22	-0.01	-0.07	45
Lleida	-0.33	0.08	-0.51	-0.37	0.24	-0.20	0.08	20
Eastern Ontario	-0.18	-0.07	-0.03	-0.43	-0.21	-0.32	-0.32	44
PVDS	-0.16	-0.15	-0.08	-0.41	-0.28	-0.46	0.29	62

We built a model similar to model 1 including both SNL and MFS in order to disentangle their effects on multitrophic diversity:

*Model 7: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + SNL + (1| Region/Year))*

Model selection based on model 7 included the same variables as for model 1 (except Latitude and SNC²), plus SNL. SNL was marginally significant. Parameter estimates and significance for variables of interest remained unchanged (Table S5.8). This results does not confirm the general assumption that the positive effect of MFS is only due to the positive effect of the amount of SNL.

Our variable SNL included a variety of semi-natural linear elements (e.g. hedgerows, grassy margins) that may not play the same role for biodiversity. Therefore, we built another model similar to model 7 including the length of hedgerows (Hedgerow) instead of SNL in order to test whether the effect of MFS on multitrophic diversity may be due to the increase in the length of hedgerows:

*Model 8: lmer (T60.landscape ~ CD * MFS * SNC + CD² + MFS² + SNC² + CropNb + Lat + Lon + Hedgerows + (1| Region/Year))*

Model selection based on model 8 included the same variables as for model 1 (except SNC² and MFS:SNC), plus Hedgerows. Hedgerows were non-significant. Parameter estimates and significance for variables of interest remained unchanged (Table S5.8). This results does not confirm the general assumption that the positive effect of MFS is only due to the positive effect of the amount of SNL or hedgerows. Instead, this result lends support to the idea that agricultural landscapes with smaller fields provide better access to different field types for species that require landscape complementation.

Table S5.8. Comparison of models 1, 7 (with SNL) and 8 (with Hedgerows) based on the uncorrelated subset of landscapes. Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 1 (subset)	model 7 – SNL	model 8 – Hedgerows
Crop diversity (CD)	-0.14 [-2.9 ; 2.62]	0.39 [-2.39 ; 3.17]	-0.03 [-2.8 ; 2.74]
Mean field size (MFS)	-9.9 [-18.1 ; -1.68] *	-8.92 [-17.24 ; -0.61] *	-8.28 [-16.94 ; 0.38] °
Semi-Natural Cover (SNC)	3.09 ; 0.15 ; 6.03] *	3.16 [0.25 ; 6.07] *	3.17 [0.21 ; 6.14] *
Latitude		2.94 [-3.03 ; 8.9]	
Longitude	2.61 [-2.01 ; 8.89]	2.06 [-4.5 ; 8.62]	2.74 [-4.1 ; 9.58]
MFS²	6.71 [-0.07 ; 13.49] °	6.54 [-0.16 ; 13.24] °	6.33 [-0.44 ; 13.11] °
SNC²		2.71 [0.14 ; 5.34] *	2.6 [-0.03 ; 5.24] °
Nb of Crops sampled	3.87 [1.58 ; 6.17] ***	4.28 [1.98 ; 6.58] ***	3.86 [1.57 ; 6.15] **
CD :SNC	1.85 [-0.28 ; 3.98] °	1.79 [-0.31 ; 3.89] °	1.83 [-0.29 ; 3.96] °
MFS :SNC	0.66 [-2.01 ; 3.32]	0.83 [-1.81 ; 3.47]	
SNL		3.64 [-0.06 ; 7.34] °	
Hedgerows			2.69 [-0.22 ; 5.56] °

5.6 Correlations and alternative mechanisms at the field level

Crop diversity and mean field size are also likely to be correlated with several variables at the field level, including the identity of crops sampled, the local land-use intensity (e.g. herbicide use, ploughing frequency). Disentangling the role of crop heterogeneity from the effects of these other variables is also necessary in order to infer potential mechanisms explaining the positive effect of crop heterogeneity on multitrophic diversity. This required running models at the field level, using a data subset for which co-variable data were available. As a result, we could not include all these variables in a single model and therefore present these analyses as separate, complementary analyses.

5.6.1. Role of the identity of sampled crop types

We tried to limit correlations between the two crop heterogeneity gradients and the identity of sampled crop types. In some cases, correlations were impossible to avoid because some crops occurred or were dominant only in some regions (e.g. rice in Camargue, almond and olive in Lleida) or some landscapes (e.g. landscapes with low crop compositional heterogeneity). As a result, different types of crop sampled were associated with significantly different values of crop diversity or mean field size (Table S5.9).

Table S5.9. Analysis of variance showing the relationship between the two heterogeneity gradients (crop diversity and mean field size) and sampled crop type within each region. Since sampled crop type is a categorical variable, correlation coefficient cannot be used. We therefore used the function aov in R, crop diversity and mean field size being the response variables and sampled crop type being the predictor variable. Values correspond to the F value of the function aov in R. * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

	Crop diversity	Mean field size
All regions	5.78***	9.28***
Armorique	1.95	0.29
Camargue	8.54**	0
Coteaux	1.16	0.59
East Anglia	3.35***	1.29
Goettingen	0	0
Lleida	9.43***	2.18
Eastern Ontario	2.57*	2.61**
PVDS	0.35	0.53

To evaluate whether the sampled crop type influenced our results, we built a model similar to model 1 but using multidiversity calculated at the field level as the response variable (T60.field). We compared models with and without adding crop type as a random effect (using data collected in 1305 fields in 435 landscapes from 8 regions). Crop type was added as a random effect because we were not interested in estimating the specific effect of each particular crop type. Note there were enough crop types (16) to estimate the random effect adequately.

*Model 9: lmer (T60.field ~ CD * MFS * SNC + CD² + MFS² + SNC² + Lat + Lon + (1| Region/Year/Landscape))*
*Model 10: lmer (T60.field ~ CD * MFS * SNC + CD² + MFS² + SNC² + Lat + Lon + (1| Region/Year/Landscape) + (1|Crop type))*

To test whether crop type had a significant effect on field-level multitrophic diversity, we used a restricted likelihood-ratio test based on simulated values from the finite sample distribution available in the function exactRLRT from package RLRsim. We then compared the estimates and p-values associated with models 9 and 10 to determine whether any effects of crop type influenced our conclusions regarding the effects of crop heterogeneity on multitrophic diversity.

Although we detected a significant effect of crop type on field-level multitrophic diversity (RLRT = 125.43, p-value < 0.001), adding crop type as a random effect in the model did not change the outcome of model selection or the significance of variables of interest (Table S5.8). This result suggests that variations in the identity of crops sampled do not explain the effects of CD, in combination with SNC, and MFS on multitrophic diversity detected in our study.

Table S5.10. Comparison of models built at the field level for multitrophic diversity (model 9 – field level, i.e. without sampled crop type as a random effect; model 10 – sampled crop id, i.e. with sampled crop type as a random effect). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° $p<0.1$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

	model 9 (field)	model 10 (field) – sampled crop ID
Crop diversity (CD)	0.78 [-0.79 ; 2.36]	0.25 [-2.08 ; 2.58]
Mean field size (MFS)	-3.14 [-6.57 ; 0.28] °	-2.44 [-4.77 ; -0.10] *
Semi-Natural Cover (SNC)	3.14 [-1.12 ; 7.4]	3.79 [0.98 ; 6.60] **
Latitude	0.97 [-3.4 ; 5.33]	
Longitude	3.63 [-1.68 ; 8.93]	1.2 [-4.88 ; 7.28]
CD²		0.67 [-4.25 ; 5.6]
MFS²	2.07 [-1.52 ; 5.66]	1.19 [-2.38 ; 4.76]
SNC²	2.9 [-1.27 ; 7.06]	2.05 [-2.08 ; 6.18]
CD :SNC	1.35 [0.08 ; 2.63] *	1.39 [0.14 ; 2.63] *
MFS :SNC	1.55 [0.09 ; 3.00] *	1.91 [0.47 ; 3.34] **
CD :MFS		0.2 [-1.12 ; 5.56]

5.6.2. Role of crop heterogeneity in cereal fields

To further assess the role of crop identity, we applied model 9 to the subset of data collected in cereal fields. Indeed, cereal is the most widespread crop type sampled in our dataset and the only one present in all regions. We therefore applied model 9 to data collected in 615 fields in 334 landscapes in our 8 regions (after removing the random effect of landscape since most landscape contain only one cereal field). This analysis confirms that decreasing MFS and, when SNC is high enough, increasing CD have positive effects on multitrophic diversity in cereal crop fields (Table S5.11).

Table S5.11. Comparison of models built at the field level for multitrophic diversity (model 9) with the complete dataset and with the cereal subset. Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 9 (field) – complete dataset	model 9 (field) – cereal subset
Crop diversity (CD)	0.78 [-0.79 ; 2.36]	-2.78 [-8.62 ; 3.06]
Mean field size (MFS)	-3.14 [-6.57 ; 0.28] °	-4.51 [-9.24 ; 0.23] °
Semi-Natural Cover (SNC)	3.14 [-1.12 ; 7.4]	3.16 [0.26 ; 6.06] *
Latitude	0.97 [-3.4 ; 5.33]	
Longitude	3.63 [-1.68 ; 8.93]	2.03 [-0.87 ; 4.94]
MFS²	2.07 [-1.52 ; 5.66]	3.62 [-0.19 ; 7.43] °
SNC²	2.9 [-1.27 ; 7.06]	1.49 [-3.09 ; 6.08]
CD :SNC	1.35 [0.08 ; 2.63] *	1.76 [0.17 ; 3.36] *
MFS :SNC	1.55 [0.09 ; 3.00] *	3.31 [1.73 ; 4.9] ***
CD :MFS		0.46 [-1.17 ; 2.09]

5.6.3. Role of field-level Land-Use Intensity

Land-use intensity may be correlated with crop heterogeneity in some regions. For instance, landscapes with larger mean field sizes may be associated with higher fertilizer inputs (Levers et al. 2016, Roschewitz et al. 2005). Such correlations could hamper our ability to draw conclusion on the effects of crop heterogeneity on multitrophic diversity.

We conducted farmer surveys to collect data on land use intensity of the sampled fields. Information included ploughing (0=no/1=yes), use of fertilizer (0=no/1=yes), frequency of herbicide use (from 0 to 7) and frequency of insecticide use (from 0 to 6) in 324 fields located in 132 landscapes across five regions (Armorique, Camargue, Coteaux, Goettingen and Eastern Ontario). We calculated a local Land-Use Intensity index (local LUI) based on the normalized mean of these four variables (after scaling each variable) following a formula similar to the one developed by Herzog et al. (2006): LUI = ¼ (scale(ploughing) + scale(fertilizer) + scale(herbicide) + scale(insecticide)). This local LUI index therefore varies between 0 (low intensity) and 1 (high intensity).

The Pearson correlation between local LUI and crop diversity was weak and not significant (r=0.10; p=0.12). The Pearson correlation between local LUI and mean field size was negative (i.e. opposite to expectation; r= -0.27; p<0.001; Fig. S5.4).
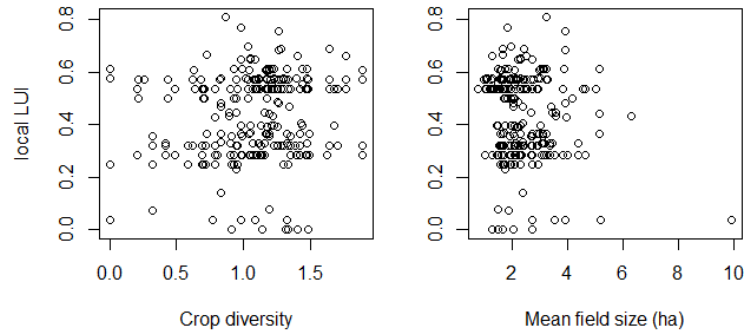
Figure S5.4. Relationship between the two crop heterogeneity gradients and Land-Use Intensity (LUI).

We added local LUI to model 10 and compared the outcomes of model 10 and model 11 using the data subset for which Field LUI data was available.

Model 11: lmer (T60.field ~ CD * MFS * SNC + CD² + MFS² + SNC² + Lat + Lon + Field LUI + (1| Region/Year/Landscape) + (1|Crop type))

Model selection based on model 11 included almost the same variables as for model 10, plus Field LUI, which had a significant negative effect. Parameter estimates for model 10 using the LUI data subset differ slightly from parameter estimates obtained for model 10 using the entire dataset due to the fact that more complex interactions were included when using the subset. Although MFS appeared to have a positive effect in model 10 using the data subset, it is important to keep in mind that this effect cannot be interpreted without taking into account the effect of MFS². The overall shape of the relationship between MFS and multitrophic diversity based on model 10 using the subset (including the quadratic effect) confirms that this relationship does not differ much between the model based on the whole dataset and the model based on the LUI dataset. More importantly, parameter estimates and significance for other variables of interest remained very similar between model 10 and model 11 (Table S5.12). This result suggests that the effects of mean field size and crop diversity cannot be explained by variations in field-level land-use intensity. It is interesting to note that we observe here a significant negative interaction between crop diversity and mean field size which is consistent with the 'landscape complementation' hypothesis, i.e. the fact that multitrophic diversity benefit more from increasing crop diversity when fields become smaller and can be reached more easily. However, the fact that this relationship was not observed in other models calls for further investigations.

Table S5.12. Comparison of models built at the field level for multitrophic diversity with and without field-level land use intensity (LUI). Parameter listed are those retained in the model selection procedure. Parameter estimates and confidence intervals are based on the model averaging approach. ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001.

	model 10 (field level LUI subset)	model 11 (field level LUI subset) - LUI
Crop diversity (CD)	18.1 [5.35 ; 20.85] **	16.14 [3.42 ; 28.86] *
Mean field size (MFS)	8.81 [0.31 ; 17.31] *	8.32 [-0.41 ; 17.05] °
Semi-Natural Cover (SNC)	17.69 [6.26 ; 29.12] **	19.11 [7.9 ; 30.33] ***
Latitude	4.38 [0.95 ; 7.82] *	5.91 [1.72 ; 10.09] **
Longitude	2.98 [-0.19 ; 6.15] °	
CD²	-15.54 [-27.25 ; -3.83] **	-14.25 [-25.88 ; -2.61] *
MFS²	-12.27 [-21.8 ; -2.7] *	-13.33 [-22.78 ; -3.88] **
SNC²	-15.76 [-27.97 ; -3.54] *	-17.9 [-29.89 ; -5.91] **
CD :SNC	-4.8 [-8.53 ; -1.06] *	-5.2 [-8.86 ; -1.55] **
MFS :SNC	2.55 [-0.77 ; 5.86]	
CD :MFS	-4.06 [-7.55 ; -0.57] *	-3.8 [-6.71 ; -0.87] *
CD :MFS :SNC	1.6 [-0.99 ; 4.19]	
Field LUI		-2.53 [-4.79 ; -0.26] *

5.7. Moving window modeling approach for Crop heterogeneity × Semi-natural cover interaction

We used a moving window modeling approach (Humpries et al. 2010; Berdugo et al. 2018) to identify potential discontinuities in the response of multitrophic diversity measured at the landscape level (T60.landscape) to crop diversity and mean field size along the gradient of semi-natural cover. To do so, we ordered all landscapes (n =

435) along the gradient of semi-natural cover (%) and selected the first 75 landscapes with the lowest semi-natural cover. Using this subset, we ran the model obtained from the averaging approach applied to model 1 (Fig. 2A main text) after excluding semi natural cover and its interactions with CD and MFS, such as:

Model 12: lmer (T60.landscape ~ CD*MFS + MFS² + CropNb + Lat + Lon + (1| Region/Year))

We then extracted and stored the model coefficient for crop diversity (CD), mean field size (MFS) and the confidence intervals (CIs). We then removed the landscape with the lowest value of semi-natural cover from the subset of 75 landscapes, added the landscape scoring the next higher value, ran model 12 and extracted model coefficients and CIs. We repeated this loop as many times as landscapes remained along the entire gradient of semi-natural cover (n = 286 subsets, see R code below). We saved all coefficients and confident intervals for each step and plotted them against the gradient of semi-natural cover (Fig. S5.5).

Consistently with our multiple regression analyses (Fig. 2A in main text), this moving window analysis showed that the effect of crop diversity and mean field size on multitrophic diversity changes along the gradient of semi-natural cover (Fig. S5.5 A and B). The effect of crop diversity is positive for high values of semi-natural cover, neutral as semi-natural cover decreases and negative for the low values of semi-natural cover. The effect of mean field size is neutral for the high values of semi-natural cover and negative for low values of semi-natural cover.

However, this analysis reveals that changes in the effect of crop diversity and mean field size on multitrophic diversity are not smooth but instead show abrupt transitions when semi-natural cover decreases. For crop diversity, there is an abrupt change at 11.2% of semi-natural cover where the effect of crop diversity shifts abruptly from positive to neutral and one at 4.5% where the effect of crop diversity shifts from neutral to negative. For mean field size, there is one abrupt change at 8% where the effect of mean field size shifts abruptly from neutral to negative. This analysis allows identifying three thresholds that can be used to guide recommendations on how to manage the three main components of agricultural landscape heterogeneity, namely crop diversity, mean field size and the amount of semi-natural cover (see main text for more details).

R Code for the Moving Window Analysis (the code provided only concerns crop diversity)

```
##### moving window function
WindowSKR <- function(df,Factor,X,Y,formul,n=10){
  myvars<-c(Factor,X,Y)
  dftemp = df[myvars]
  dftemp = dftemp[order(dftemp[Factor]),]
  tt=length(unlist(dftemp[Factor]))-n
  i = 1
  mdl <- lmer(data = dftemp, formula = formul)
  res<- matrix(data = NA,nrow = 1,ncol = length(fixef(mdl))+1)
  ci<-res
  library(lme4)
  while(tt>n){
    dfi <- dftemp[i:(i+n),]
    Fact <- mean(unlist(dfi[Factor]))
    mdl <- lmer(data = dfi, formula = formul, na.action = na.fail,REML ="TRUE")
    #dist<- mean(unlist(dfi[X]))+1-mean(unlist(dfi[Y]))
    res <- rbind(res,c(Fact,fixef(mdl)))
    cii <- (abs(confint(mdl)[-c(1,2),1]-confint(mdl)[-c(1,2),2]))/2
    ci<-rbind(ci,c(Fact,cii))
    tt=tt-1
    i=i+1
  }
  res<- as.data.frame(res)
  ci<-as.data.frame(ci)
  colnames(res)<-c("MWfactor",names(fixef(mdl)))
  colnames(ci)<-c("MWfactor",names(fixef(mdl)))
  RES<-list(res=res,ci=ci)
  return(RES)
}

##### uploading libraries
library(jsonlite)
library(ggplot2)
library(tidyr)
```

```
library(boot)
library(lme4)

#### running moving window analysis
formul<-T60.landscape~ Crop_SHDI+Crop_MFS + sampled.crop.nb + MFS2 + Lon + Lat +  (1|Region/Year) -1
RES   <-   WindowSKR(df,"Seminat_Cover",c("Crop_SHDI","MFS2","Crop_MFS",   "Seminat_Cover",   "sampled.crop.nb",
"Region", "Year", "Lon", "Lat"),"T60.landscape",formul,n=75)

#### plotting results of the moving window analysis
dfres=data.frame(MWfactor<-RES$res$MWfactor, Effect<-RES$res$Crop_SHDI, CI<-RES$ci$Crop_SHDI)
limits <- aes(ymax = Effect + CI, ymin=Effect - CI)
p1<-ggplot(data = dfres,aes(x = MWfactor,y = Effect), ylim = c(1,4))+
 geom_line(col = "olivedrab3")+
 geom_point(col = "olivedrab3")+
 geom_pointrange(limits,col = "olivedrab3")+
 xlab("Semi-Natural Cover (%)")+
 ylab("Effect of Crop Diversity")
p1  +  theme(axis.text=element_text(size=14),  axis.title.x  =  element_text(size=18,  face="bold"),  axis.title.y  =
element_text(size=18, face="bold"))
```
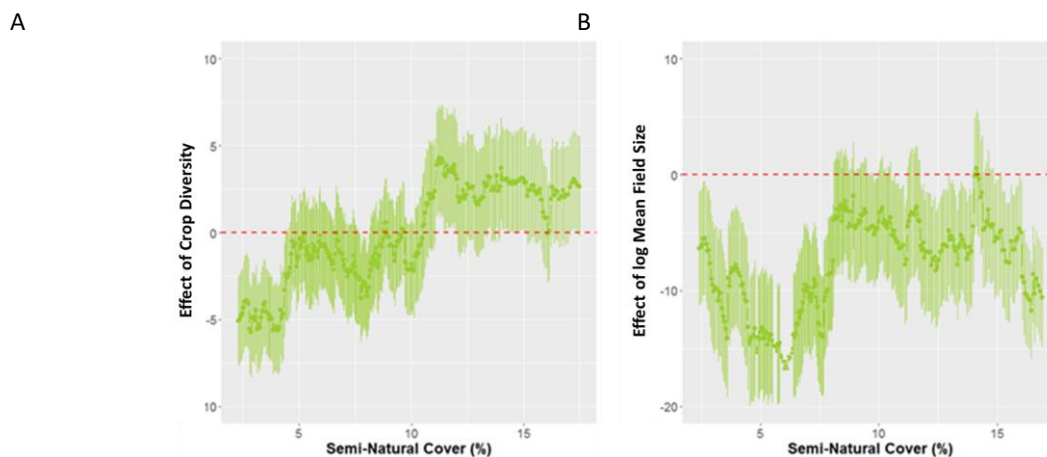

Figure S5.5. Effect of crop diversity (A) and mean field size (B) on multitrophic diversity for different levels of semi-natural cover. Parameter estimates and confidence intervals are based on a moving window analysis (see detailed description in SI5). The red line indicates a null effect. Each dot and CI correspond to the estimate values of CD or MFS for the average semi-natural cover of a given window along the semi-natural cover gradient. Due to the low number of landscapes with semi-natural cover >17.5% (Table S4.1), we only represent the gradient between 0 and 17.5% of semi-natural cover on these figures.

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