

REGIONAL CROP ROTATIONS FOR ECOLOGICAL PEST MANAGEMENT (EPM) AT LANDSCAPE LEVEL

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ABSTRACT

Spatiotemporal scales and landscape heterogeneity are known to play crucial role in (meta)population dynamics of many kinds of organisms. The theory of conservation of species can be reversed for purposes of EPM, Ecological Pest Management. Many pest species of annual arable crops are essentially species of early successional habitats. In addition, many have low to moderate dispersal ability. Such pest species can be expected to form true metapopulations of the Levins's 1969 classic model, in the sense that the persistence is dependent on between-population rather than within-population processes. Adjustment of the spatial and temporal scale of rotation to help drive pests into local extinction is a management alternative in annual arable cropping. In such ephemeral habitats, true regulation of populations by specialist natural enemies is not achievable. By planning at a landscape level, benefits of regional pest management as an essential part of EPM can be combined to bring benefits of improved logistics and economy of scale, which may provide sufficient incentive for the necessary local cooperation between farmers.

INTRODUCTION

The term metapopulation was first introduced by Levins (1970) to mean a population of populations which go extinct locally and recolonize. This conceptual innovation was published a year earlier, when Levins (1969) presented his metapopulation model. For twenty years, the concept was largely ignored, but then the interest was renewed (for the history, see Hanski & Gilpin, 1991). The main area of motivation for theory development and the main area of applications has been for several years in conservation biology. However, Levins's (1969) concern was in pest control: he noticed that local populations would fluctuate in asynchrony, and the model predicted that control should be concerted throughout a region in order to decrease the size of metapopulation and hence, in order to reduce future control investment. Levins emphasized this area of application again later (1970), by stating that extinction is fundamental to any theory to pest control, and that it is in the field of economic entomology that long term studies over wide areas of real populations can be done.

It is obvious that much of the theory development done in the field of conservation biology is directly applicable to pest control problems, just by reversing the goal of conservation into the goal of extinction. Moreover, there seems to be more scope and more urgent need for such applications in Ecological Pest Management (EPM), in which chemical 'quick fixes' are at present not an option, than in Integrated Pest Management (see also Helenius, 1995a).

ECOLOGICAL PEST MANAGEMENT, EPM

EPM is defined here as a pest management approach that sets ecological sustainability as a starting point and ecology as a scientific base. It is fundamentally different to Integrated Pest Management, IPM, in the sense that it does not compromise over the primary criteria. Towards use of pesticides, IPM takes a liberal view: 'gains must be greater than losses'. It represents understandable consensus among interests of pesticide industry, conventional agriculture and applied science. In EPM, the cumulated knowledge of ecological side-effects of pesticide use is enough for taking a more strict view. Taking sustainability seriously, the short-term economic gains must not dictate the strategy.

EPM is a scientific approach suited to all production systems: of course, to organic (ecological) farming, but also to integrated farming, pesticide free farming and even to conventional farming. Chemical options are not excluded, but a safe pesticide is awaiting. The landscape level pest control strategy described in this paper serves as an example of EPM-oriented approach.

REGIONAL STOCHASTICITY AND METAPOPOPULATIONS OF PESTS

Regional stochasticity (Hanski, 1991) is a metapopulation concept that refers to chance effects that are regionally correlated between local populations. In general, metapopulation persistence is decreased by increasing regional stochasticity (Hanski, 1991). Conventionally, crop fields are managed within units of single farms: at any level that exceeds single farm boundaries, there is little or no regional stochasticity in habitat availability to pest organisms. Crop fields that are suitable to a pest blink on and off from season to season in a spatially uncorrelated manner.

In Levins' (1969) model, dynamics of $p(t)$, the fraction of habitat patches occupied by the species at time t is described as

$$dp/dt = mp(1-p) - ep,$$

where e and m are the rates of local extinction and colonization of empty patches, respectively (notation from Hanski & Gilpin, 1991). In this model, regional stochasticity is affected by manipulation of e . Best control would be achieved by maximizing temporal variance of a regionally uniform extinction rate, in other words, by increasing regional stochasticity. From this result, Levins (1969) outlined a strategy of applying chemical control measures over large regions simultaneously. This would result in decrease in average size of the metapopulation of the pest.

The process outlined by Levins (1969) is not, however, quite analogous to such a regional stochasticity that is achieved by regionally correlated crop rotation. In regional rotations, local extinctions are achieved by crop (habitat!) patch removals and rearrangements, not by control of local populations within patches. Of course, patch removals produce local extinctions, and if these are synchronized temporally over the region, then at an extreme e approaches 1, control is complete in one season, and no attention needs to be paid into manipulation of m .

EFFECTS OF PATCH SIZE, PATCH NUMBER AND PATCH ISOLATION

It is quite obvious that increased distance (isolation) between local pest populations, i.e. increased distance between occupied habitat patches, decreases naturally occurring regional stochasticity; for example, catastrophes due to extreme weather seldom cover wide regions. But let us focus on colonization for a while.

In practice, the colonization parameter m is also subject to manipulation by regional rotations. The distance between crop patches is directly affected. Any effects on local population densities is likely to affect m as well, through the number of potential colonists. Levins (1969) already noted, that if the strategy relies in reducing migration rate, the recommendations for control are opposite of those for control by increasing local extinction rate.

Using model (1) as a starting point, Hanski (1991) studied the effects of patch size, number and isolation in relation to metapopulation extinction. The most fundamental cause for extinction would be lack of positive equilibrium point in model (1): when p is small, m is lower than e . In this scenario, decreasing the size of habitat patches increases extinction rate, and increasing the isolation of habitat patches decreases colonization rate (number of colonists produced is assumed to be directly proportional to patch size).

As a metapopulation parallel to demographic stochasticity (chance events of death and birth that are uncorrelated between individuals in a local population), Hanski (1991) coined the term immigration-extinction stochasticity to mean the chance extinctions of local populations that are uncorrelated between the populations. As a cause of metapopulation extinction, immigration-extinction stochasticity is dependent on number of habitat patches. If the number of habitat patches is small and extinction probability is not negligible, a metapopulation may go extinct simply because all local populations happen to go extinct at the same time.

For more details of the theoretical background, see Hanski (1991) and references therein.

CROP ROTATION AT A LANDSCAPE LEVEL FOR PEST CONTROL

Perhaps the most obvious alternative for regional rotation is to reduce number of host crop fields by aggregating the desired area of production into a small number of more isolated but, inevitably, large crop field patches. The idea would be to generate aggregates of field parcels within which, the pest would form single local populations (see Helenius, 1995a), and to rotate these aggregates regionally to new sites each season.

Replacement of the large number of within-farm rotated crop patches with small number of regionally rotated patches of same total area of production increases isolation. In theory, isolation increases metapopulation persistence by reducing regional stochasticity and by increasing local population size, and at the same time, it decreases persistence by increased migration distances and migration losses. However, regional stochasticity from natural causes is likely to be of minor importance: the 'managed' regional stochasticity at its extreme operates through concerted removal and spatially unpredictable re-establishment of the habitat itself, in each season.

The latter two effects are relevant to the 'no positive equilibrium'-scenario of metapopulation extinction. In the theory, 'local population size' refers to number, not to density of specimens. Even if in nature, large patches support large populations least prone to extinction, does this undermine the 'aggregate-rotation' strategy? The theory refers to stable

habitat patches or patch mosaics with low turnover rate (in relation to generation turnover of the species). However, the rotated habitat 'patches', i.e. the crop field aggregates of the regional rotation are highly ephemeral. Obviously, the point of larger populations being supported by large patches is of no or minor relevance to the application discussed here. On the contrary, positive implications of increased size of crop blocks may include 1) dilution effect, as the remaining crop colonizers are overwhelmed by the abundance of host plants, and 2) reduced edge effect (tendency of many pest problems concentrating to crop margins) due to decreased area to perimeter ratio.

Spatial and temporal scales and patterns of landscape level rotations for pest control combine to a large potential set of designs. From general ecological and agricultural knowledge, only broad rules can be derived for what would be a good strategy for each individual case. Much depends on properties of the crop and pest in question.

FOR WHAT KINDS OF PESTS AND CROPS?

First, it is important that the pest does not have large source populations in natural habitats scattered among the crop habitats. The second important criteria is the dispersal range and rate of the pest. In most circumstances, regional management is more likely to succeed with species with low or moderate dispersal range, than with species capable of dispersing across the entire landscape in a short period of time. The third criteria is the frequency and regularity of outbreaks: most effort should be spent into pests that are common and cause regular damage. However, occasional 'rare' pest species may well turn out to be best targets for region-wide 'eradication' schemes.

Fourth and equally important; the spatial range and distribution and temporal range and regularity of the crop host must be considered. Widely grown, uniformly distributed major crops cannot be rotated regionally: good examples are cereal crops in most areas worldwide. High-valued crops that are common but occupy a relatively small proportion of the land may in most cases best suit to regional rotation strategy. Many vegetable crops may be well suited to such an approach.

COMPATIBILITY WITH BIOLOGICAL CONTROL

The role of natural enemies depends on the spatial and temporal patterns of the pest and the crop. May (1994) developed a simple predator-prey metapopulation model that supports the intuition that habitat removal decreases persistence of specialized natural enemies more than persistence of the pest. May's (1994) model predicts that decreasing the number of habitat patches in a landscape results in steady decrease in proportion of remaining patches being occupied by the specialist enemy, until at some stage, defined by the model parameters, the natural enemy is extinguished. The proportion of remaining patches occupied by pest only first increases, but after the enemy goes extinct, due to extinction rate of local host populations, the proportion of patches occupied by the host declines until the host also goes regionally extinct.

In the regional rotation based on aggregating the crop fields into few large patches, the total area of habitat does not decrease, as it does in May's (1994) model. The model does not account for a situation in which the number of patches decreases, but at the same time, the size of the patches increases. However, the modelling exercise warns about problems that various

regional rotation schemes may cause to biological control. How real is this threat?

Most pest species of annual arable crops are exploiters of early successional habitats. In cases when the dispersal ability of the species is relatively low in the regional scale, such species can be expected to form 'true' metapopulations (*sensu* Harrison, 1991) of the Levins's (1969, 1970) classic model. In other words, the persistence of the species is dependent on between-population rather than within-population processes (Harrison, 1994). This conclusion has three important implications in favour of management by regional rotation.

The first is that only metapopulations that behave according to the Levins model lend themselves to regional management, be it conservation (Harrison, 1994) or pest control. Secondly, according to the synoptic model of how predation may interact with habitat stability in the population dynamics of a pest (Southwood & Comins, 1976), for pest species of ephemeral arable crops that are from the r-end of the r-K continuum, the reproductive numerical response of natural enemies to 'booming' pest density is limited. Thus, within the 'natural enemy ravine', i.e. the range of population growth rate of the pest within which biocontrol is effective, the significant predators are often polyphagous and large relative to their prey, and occur at relatively low densities (Southwood and Comins, 1976). This implies that the key predator species would be large voracious generalists. Generalists are not coupled to a one pest as prey and, as a consequence, would not be suppressed by regional rotation.

The third implication is related to the previous ones: because individual fields of annual arable crops are maintained in nonequilibrium, there are no grounds for exploring equilibrium solutions for pest-enemy interactions anyway (Murdoch, 1975). This view was also supported, although perhaps implicitly, by Beddington *et al.* (1978) in their characterization of successful natural enemies (for further discussion, see Helenius, 1995b). Good empirical evidence comes from records of success in classical biological control (Hokkanen, 1985).

Thus, the pest species that are likely candidates to management by regional crop rotation are, fortunately, the ones not regulated by specialist enemies. In fact, the prerequisites for successful regional management contrast the prerequisites for natural control by specialist enemies. The host crop-pest systems most promising for the strategy are the least promising for classical biological control. Of course, 'buffering' the crops against colonizing pests by enhancement of generalist predator complex is compatible with regional rotation. For conclusions concerning traits of an effective predator in control of model metapopulations of pests, see Levins (1969)!

CONCLUSIONS

Regional crop rotation for pest control is an example from a wide array of strategies based on landscape level management. If appropriately planned, it can increase energy efficiency and improve logistics of crop production as a whole.

Questioning the role of single farms as optimal management units has several socioeconomic implications. However, the effort should be made as, traditionally, the optimal use of natural resources has not been the criteria for land allocation. Modern techniques of landscape ecology facilitate the design of idealized landscapes on several simultaneous criteria (Lenz & Stary, 1995). Of course, the implementation of landscape level strategies requires political will and new forms of cooperation between farm enterprises.

More research is required on metapopulation dynamics of pest species and their natural enemies than is currently in progress. Modelling approaches will be necessary, because

experimentation with farmers' fields at a regional level is seldom possible. Good evidence of effectiveness and prediction of how many seasons is required before the pest decline reaches the desired level are required before introducing such schemes for widespread practice. However, as no great risks are involved, farmers' own experimentation can be encouraged.

Recent development in population biology and its application to conservation of species certainly points towards a novel pest management strategy. The strategy should prove especially useful for ecological pest management in organic (ecological) farming where pesticides are abandoned and sustainability is emphasized.

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THE EFFECTS OF ORGANIC AND CONVENTIONAL SYSTEMS ON THE ABUNDANCE OF PEST AND NON-PEST BUTTERFLIES

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ABSTRACT

Butterfly transects were conducted on eight pairs of organic and conventional farms in England in 1994. The abundance of each species of butterfly was recorded. Organic systems increased overall butterfly abundance, and more non-pest butterflies were recorded on the margin than the crop. By contrast, there was no significant difference in the abundance of two pest species, *Pieris brassicae* (the large white) and *Pieris rapae* (the small white) between the two systems on either the crop or the margin habitat. Patterns of crop use by pest and non-pest butterflies differed significantly.

INTRODUCTION

Recent years have seen shifts in agricultural policy in Europe, resulting primarily from overproduction, together with consumer concerns about the environment and the way in which food is produced. Organic farming is the extreme expression of low-input agriculture and has become a small, but established, part of the agricultural scene. While organic agriculture continues to attract technical research (summarised in Lampkin, 1990), studies of the effects of organic farming systems on wildlife populations in the UK have so far largely been restricted to birds and their insect food resources (e.g. Wilson & Browne, 1993). In this paper we report on a study of butterfly abundance on organic and conventional farms in 1994.

Of the butterfly species resident in Britain, only the large white (*Pieris brassicae*) and the small white (*Pieris rapae*) are significant agricultural and horticultural pests. The damage inflicted by the larvae of both of these species on their cruciferous hosts may run to millions of pounds sterling annually (Feltwell, 1980). The remainder of the British butterfly species are agriculturally benign and, by contrast to the two pest species, are frequently targeted for conservation measures within habitats such as woodland and grassland reserves (Thomas 1984). Increasingly, butterflies are also the subject of conservation interest in the wider countryside (Dover *et al.*, 1990; Feber & Smith, 1995; Feber *et al.*, 1994) where agricultural intensification has led to large-scale losses of semi-natural habitats (Anon., 1984). In this paper we present results which show the effects of organic and conventional farming management on the abundances of non-pest and pest butterflies within agricultural systems.

METHODS

Butterfly abundance was recorded on eight pairs of organic and conventional farms between June and September in 1994. Farm pairs were located across England in an area roughly bordered by Dorset, Shropshire, Lincolnshire and Essex. Butterflies were recorded by experienced volunteer recorders at approximately fortnightly intervals during the summer, following methods modified from those described by Pollard (1977) and Pollard *et. al.* (1975), which are used in the National Butterfly Monitoring Scheme. Volunteers walked a fixed transect route which was divided into sections corresponding to crop and/or boundary type. For each section, all butterfly species seen, and the abundance of each species, was recorded. Butterflies seen over the crop edge were recorded separately from those seen over the uncropped field boundary. Details of management type, crop and boundary were recorded for each section of the transect route.

Analysis

The dependent variable was defined as the total butterfly count for the season for each management type (organic or conventional) in each farm pair, on both the crop edge and the uncropped field boundary, standardised to a count per unit length of transect walked. Data were $\log(x+1)$ transformed for analysis.

Two separate analyses were carried out; the first on the total number of butterflies regardless of their pest status, and the second on the data partitioned into pest (*P. brassicae* and *P. rapae*) and non-pest (all other) individuals.

For the first analysis, a two-way analysis of variance was carried out, including management type (subsequently referred to as "management") and crop or margin ("habitat") as effects, with repeated measures for each farm pair ("site") on both effects (SAS PROC GLM; SAS Institute 1988). In the second analysis the pest status of the butterflies ("status") was included as a third effect. When significant interactions were detected, the data were stratified within the levels of the appropriate effect. Further analyses were then applied to clarify these interactions.

RESULTS

Effects of management on overall butterfly abundance

Total butterfly abundance was significantly higher on organic farms than on conventional farms ($F_{(1,7)}=8.32$, $P=0.024$; Figure 1). Significantly more butterflies were recorded on the uncropped field boundary than on the crop edge ($F_{(1,7)}=12.91$, $P=0.009$). There was a significant interaction between the two factors ($F_{(1,7)}=6.28$, $P=0.041$) with the difference in butterfly abundance between crop and margin being greater in conventional than in organic systems.

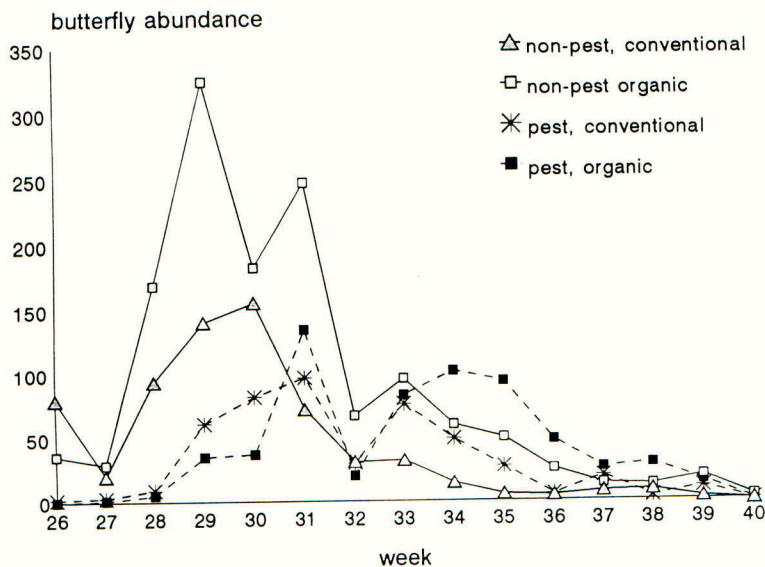


FIGURE 1. Mean pest and non-pest butterfly abundance per kilometre per site per week, on organic and conventional farmland in 1994.

The relationship between pest status and management, and butterfly abundance

The two-way interactions between pest status and management, and between status and habitat, were significant ($F_{(1,7)}=8.42$, $P=0.023$ and $F_{(1,7)}=35.23$, $P<0.001$ respectively). One-way analyses were therefore carried out separately for both levels of pest and non-pest status butterflies.

Effects of management on non-pest butterfly abundance

The abundance of butterflies, not including *P. brassicae* and *P. rapae*, was significantly higher in organic than conventional systems ($F_{(1,7)}=28.43$, $P<0.001$; Figure 1). There was a highly significant effect of habitat on the abundance of non-pest butterflies ($F_{(1,7)}=73.31$, $P<0.001$), with more butterflies recorded on the boundary than the crop. The interaction between these factors approached significance ($F_{(1,7)}=5.59$, $P=0.050$). The management of the uncropped boundary had a significant effect on non-pest abundance, with organic boundaries attracting higher numbers of butterflies than conventional boundaries. Similarly, organic management increased the abundance of non-pest butterflies within the surveyed cropped habitats ($F_{(1,7)}=28.25$, $P<0.001$).

Effects of management on pest butterfly abundance

By contrast with the non-pest species, there was no significant difference in the abundance of *P. brassicae* and *P. rapae* between the two management systems ($F_{(1,7)}=0.19$, $P=0.672$; Figure 1). The abundance of these species did not differ significantly between crop

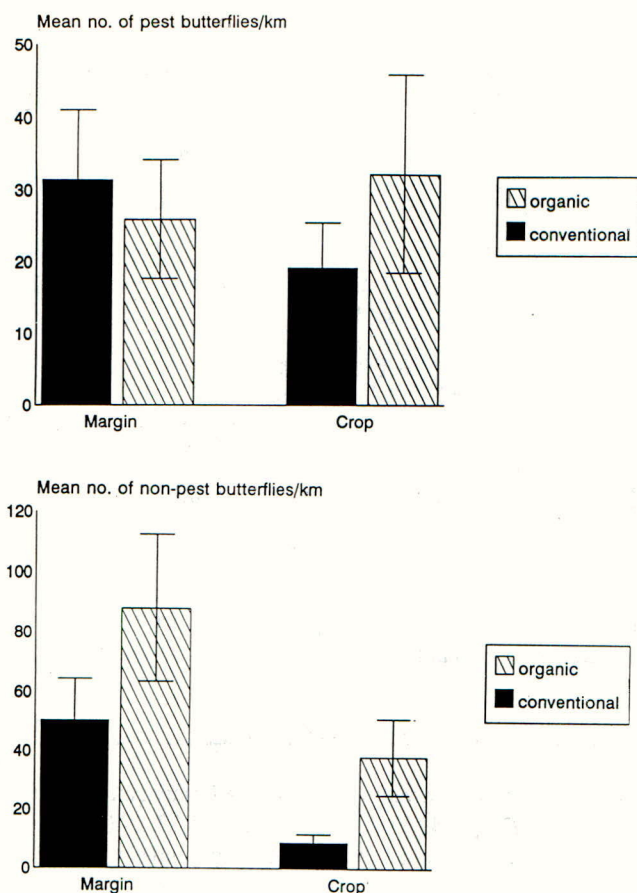


FIGURE 2. Abundance of (a) pest and (b) non-pest butterflies on crop and boundary habitats, on organic and conventional farmland.

and boundary habitat ($F_{(1,7)}=2.18$, $P=0.183$) and there was no significant interaction between the two factors ($F_{(1,7)}=1.88$, $P=0.213$). There was no significant effect of management on pest butterfly abundance within either the surveyed boundary ($F_{(1,7)}=0.17$, $P=0.692$) or crop ($F_{(1,7)}=0.76$, $P=0.412$) habitats.

Effects of crop type on pest and non-pest butterfly abundance

The cropping patterns on the surveyed sites differed considerably between the organic and conventional components. For example, approximately six times as much grass ley was surveyed on the organic areas than the conventional areas, while oilseed rape was not encountered on any organic area (Table 1).

TABLE 1. The lengths of each crop type surveyed, and the mean abundances of pest and non-pest butterflies per kilometre, per transect, on each crop type. Crop types not present on both organic and conventional not included in the analysis.

Crop	System	Length of crop type surveyed (km)	Mean pest abundance	Mean non-pest abundance
winter wheat	organic	3.16	2.95	6.59
	conventional	3.42	2.16	1.61
barley	organic	-		
	conventional	0.18	6.04	0.00
oats	organic	0.66	7.71	20.43
	conventional	-		
linseed	organic	-		
	conventional	0.68	13.42	0.15
oilseed rape	organic	-		
	conventional	0.62	7.16	4.48
beans	organic	0.80	8.50	1.61
	conventional	2.40	17.79	4.93
grass ley	organic	7.14	2.12	13.70
	conventional	1.47	1.13	4.48
set-aside	organic	0.69	12.63	24.29
	conventional	0.12	6.97	15.10

The patterns of crop use by pests and non-pests were significantly different (interaction between status and croptype: $F_{(3,4)}=20.98$, $P=0.002$). Pests were more abundant on beans than non-pests, while non-pest individuals were more abundant on grass leys than pests (Table 1). Set-aside and cereal crops attracted similar numbers of pest and non-pest individuals. Oil-seed crops (linseed and rape) attracted higher numbers of pest than non-pest butterflies.

There was no significant main effect of management on the abundance of either pest or non-pest individuals for any crop type ($F_{(1,4)}=0.07$, $P=0.806$).

DISCUSSION

The majority of non-pest butterflies recorded on farmland are common species, usually associated with hedgerow or grassland habitats. A number of these species are relatively sedentary, and may have specific larval food requirements. The pest butterflies, *P. brassicae* and *P. rapae*, however, are highly mobile, and their larvae will feed on a wide range of cruciferous and related foodplants.

In our study, most of the non-pest butterflies were associated with the uncropped field boundary habitat. The nature of the boundary varied considerably between fields and farms but, overall, non-pest butterfly abundance was significantly higher on organic than on conventional boundaries. Absence of herbicide application to the hedge base, and better

hedgerow management, are likely to account for this result. This suggests that targeting uncropped field boundaries is perhaps the most productive conservation measure for butterflies on farmland, and this can be achieved under a range of farming systems.

By contrast with the boundary habitat, non-pest butterflies abundance did not differ significantly for any given crop type between systems, although our small sample size at this level of analysis warrants caution in interpretation. Effects of different crop management on butterflies may be complex and subtle. Weedier crops may provide more nectar resources for adult butterflies (e.g. Conservation Headlands: Dover *et al.* 1990). They may also contain larval foodplants on which butterflies oviposit but, unless the larvae can develop and hatch during the summer (only a few species complete their life cycle in such a short period), there may be considerable larval mortality at harvest. The polyphagous predator web is also affected by management. Studies have shown significantly increased predation on *P. rapae* by the presence of weeds within the crop (Dempster, 1969).

Organic systems, however, did increase the abundance of non-pest species in the cropped habitats overall. The most likely reason for this is the different proportions of crop types between the two systems. Organic farms have a higher proportion of grass leys than conventional farms. Species such as the meadow brown (*Maniola jurtina*) and the gatekeeper (*Pyronia tithonus*) feed on a range of grasses and may breed successfully on such leys if they are in place for more than one year. Thus, at a landscape level, organic farming systems may have positive implications for the conservation of butterflies on farmland.

In terms of absolute numbers, there was no significant difference between the two systems for pest butterflies. There was no significant difference between crop or boundary habitat use by the two pest species, and no effect of farming system on their abundance. Some contrasting features of the two systems, though, may account for a difference in the proportion of butterflies which were pests between the two systems. Oilseed rape, for example, is rarely found on organic farms because of its low premium and high nutrient demand. This cruciferous crop is very attractive to white butterflies and is common in conventional systems. Weedy crucifers may be out-competed in grass clover leys which form a large proportion of most organic farms. The high mobility of the pest white butterflies may allow them to use the cropped habitat to a greater extent than non-pest species, and increase the species' resilience to farming practices common in conventional systems, such as widespread herbicide use. The pest white butterflies showed no significant association with the uncropped field boundary, and so any conservation measures applied to this habitat are unlikely to increase the abundance of pest whites.

In summary, our results have shown that organic systems increased non-pest butterfly abundance overall without increasing the abundance of pest butterflies. This is likely to be due to a combination of factors, in particular, differences in cropping patterns and boundary management, and the ecological characteristics of the pest and non-pest butterflies. Whilst the rotations are intrinsic to organic agriculture, we suggest that changes in approaches to boundary management may have conservation benefits for non-pest butterflies, and be acceptable within the constraints of conventional farming systems.

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