**Agricultural landscape structure and invasive species: the cost-effective level of crop field clustering to prevent losses from invasive pests**

Martin Drechsler1, Julia Touza2, Piran C. L. White2, Glyn Jones3

*1Helmholtz Center for Environmental Research – UFZ, Department of Ecological Modeling, Permoserstrasse 15, 04318 Leipzig, Germany.*

2Environment Department, University of York, Heslington, , York, YO10 5DD, UK.

3Food and Environment Research Agency (FERA), Sand Hutton, York, YO41 1LZ, UK.

Emails: martin.drechsler@ufz.de (M. Drechsler); julia.touza@york.ac.uk (J. Touza); piran.white@york.ac.uk (P. White); glyn.d.jones@fera.co.uk (G. Jones)

**Abstract**

Invasive pests in agricultural settings may have severe consequences for agricultural production, reducing yields and the value of crops. Once an invader population has established, controlling it tends to be very expensive. Therefore, when the potential impacts on production may be great, protection against initial establishment is often perceived to be the most cost-effective measure. Increasing attention in the ecological literature is being given to the possibility of curbing invasion processes by manipulating the field and cropping patterns in agricultural landscapes, so that they are less conducive to the spread of pests. However, the economic implications of such interventions have received far less attention. This paper uses a stochastic spatial model to identify the key processes that influence the vulnerability of a fragmented agricultural landscape to pests. We explore the interaction between the divergent forces of ecological invasion pressure and economic returns to scale, in relation to the level of clustering of crop fields. Results show that the most cost-effective distances between crop fields in terms of reducing production impacts from an invasive pest are determined by a delicate balance of these two forces and depend on the values of the ecological and economic parameters involved. If agricultural productivity declines slowly with increasing distance between fields and the dispersal range of the potential invader is high, manipulation of cropping structure has the potential to protect against invasion outbreaks and the farmer can gain benefit overall from maintaining greater distances between fields of similar crops.

**Keywords:** invasive species, agricultural pests, landscape fragmentation, spatial agglomeration.

**1.- Introduction**

Biological invasions are key drivers of species extinction and global environmental change and represent an economic challenge for rural economies (e.g. Pimentel et al. 2005; Brasier 2008; Pejchar and Harold, 2009; Holmes et al. 2009; Vilà, et al. 2010). The difficulty of eradicating invasive species, and their potential cost to society, means that the most cost-effective approach to their management is generally to mitigate potential damages by adopting biosecurity measures for the prevention and containment of any further spread (e.g. Heikkila and Peltola 2004; Finnoff, et al. 2007; Wang et al. 2012). There is growing research effort into how best to target biosecurity efforts more efficiently by taking into account the spatial dimension of invasive species spread (e.g. Epanchin-Niell and Hastings 2010; Sanchirico et al. 2010; Cacho and Hester 2011). Here we focus on recent attention in the ecological literature on the potential role of landscape management as a prevention policy to curb the invasion processes (Sharov 2004; Gosper et al. 2005; Hulme, 2006).

The spatial arrangement of suitable habitats influences species movement and dispersal, and therefore the spread of invasions (With, 2002; Holdenrieder, 2004; Jeger, 2007; Crespo-Pérez et al 2011). Margosian *et al.* (2009) showed a general relationship between the overall connectivity of an agricultural landscape (abundance and configuration of land use types) and the probability of spread of introduced crop diseases or insect pests. With (2004) showed that spread is actually a result of the interaction between species dispersal characteristics and landscape structure, and that an invader with local dispersal characteristics is more likely to spread across a landscape formed by compact clusters of suitable habitats, whereas an invader with greater dispersal ability is more likely to spread across a more patchy landscape. More recent work has highlighted the non-linear nature of this relationship. For example, Skelsey et al. (2013a, b) showed that spread is maximized at an intermediate scale of landscape grain size relative to the dispersal abilities of a species. The phenomenon, which they termed the Dispersal Scaling Hypothesis (DSH), reflects the trade–off between the increasing benefits of larger patches (equating to more dispersers) and the increasing costs of dispersing over long distances in landscapes of increasing grain size (Skelsey et al. 2013b). This new understanding of the influence of landscape structure on pest distribution and dynamics has led to further ecological modelling studies to evaluate its potential application to practical pest management (e.g. Papaix et al. 2014). However, these studies tend to ignore the economic aspects of management. Farmers will need to know the extent to which any benefits they may obtain by modifying the cropping pattern on their farm, in terms of reducing the risk of invasion, will be offset by the increase in production costs associated with more dispersed crops. Linking economic models of control with ecological models of spread has been identified as one of the key challenges in the modelling of plant diseases (Cunniffe et al. 2015).

Although landscape patchiness as a management tool to reduce the impact of invasive species has attracted the interest of landscape ecologists and modellers relatively recently, landscapes have a long history of change as a consequence of various ecological, economic, cultural and historic reasons. Taking the UK as an illustration, Robinson and Sutherland (2002) state that farming practices in the UK became more intensive in the post-war period, with a large reduction in landscape diversity: since 1945, there has been a 65% decline in the number of farms, an increase in farm size, a 77% decline in farm labour and an almost fourfold increase in yield. Increased specialization has occurred with an increased use of machinery which has made operations quicker and more efficient. Other factors affecting a reduction in landscape diversity and biodiversity include the increase in overall field size by the removal of half of the hedgerow stock (to facilitate the use of machinery), the increased use of pesticides (that reduce the need for non-cereal crops to prevent pest build-up), and changes in rotation patterns (Robinson and Sutherland 2002). At the global level, land consolidation programs and land reform policies, provides us with another illustration of longer-term changes in the management of rural landscapes that have acted to reduce the fragmentation of agricultural holdings (e.g. Dijk 2003; Gajendra and Gopal, 2005; Niroula and Thapa 2005; Miranda, et al. 2006; Sklenicka, 2006; Gopal and Ganjendra, 2008; Pasakarnis and Maliene, 2010; Huang et al., 2011; Demetriou et al. 2012; Lisec et al. 2014; Sayilan 2014).

The implications of changes resulting from these socio-economic and political forces for the ecology and impacts of invasive species have not been investigated previously, but recent ecological work suggests they may be substantial. Indeed, there may be a tension between the centripetal economic forces acting to create clusters in the landscape and the centrifugal forces of ecological dispersal which result from an interplay between landscape connectivity and species dispersal characteristics.

In this paper, we use a stochastic spatial model of a biological invasion process and show that farmers’ benefits can be maximized by scattering their plots across the landscape if agricultural productivity of inputs declines only slowly with increasing distance between fields, and the dispersal range of the potential invader is high. However, if the probability of infestation from surrounding areas is unaffected by farmers’ decisions of where to plant similar crops (i.e. they cannot influence the probability of infestations from external sources, perhaps due to reduced border inspections or an infectious agent with very high dispersal ability), then policies attending to landscape structure to reduce pest dispersal and agricultural damages are not suitable.

**2.- Methods**

**2.1.- Model description**

The model represents *N* fields within a matrix of fallow fields from an agricultural holding, which are spread in a landscape, and are assumed to be identical except for their spatial location. The agricultural production is characterized by unexhausted increasing returns to scale, that is higher productivity can be achieved by concentrating agricultural fields of similar crops. This means that the farmers benefit from locating their fields of the same crop near each other, because by clustering fields, farmers would be more efficient in input utilisation (i.e., labour and machinery). This advantage depends on the distance between fields.

By concentrating fields of the same crop, the net benefit from agriculture production is determined by not just revenues and costs but also by the spatial configuration of the fields (the distance between fields). Thus the net benefit, *bm*, in any given field *m* () is defined as follows,

 (1)

where *xm* is the production output of field *m*, *p* the unit price of *x*, *a* the total fixed cost of production (i.e. an indivisible amount of overhead required for each parcel), and *f*(*d*1,*m*,*d*2,*m*,…) the average variable cost of producing a unit of *x*, which depends on the spatial configuration of the landscape with *dn*,*m* representing the distances of field *m* to the other fields  (of the same owner). This function varies between spatial configurations, and captures the incentives for farmers to concentrate fields of the same crop, following Forslid and Ottaviano (2003) and Grazi et al. (2007). Thus, due to economies of scale, the average cost *f*(*d*1,*m*,*d*2,*m*,…) is small if all fields are agglomerated (*dn*,*m* small) implying higher input productivity and lower production costs; while it is large if the fields are dispersed. For simplicity we assume the following functional shape:

 (2)

Here *z* represents the average costs that would exist if spatial efficiency gains were not exploited. Figure 1 shows that for a given value of *β,* input productivity increases (i.e. lower average costs through efficiency gains) with decreasing distance. Alternatively, for a given distance between fields of the same crop, productivity increases (i.e. lower average costs) with decreasing *β*. Thus, a low value for *β* (as shown in Figure 1 *β* = 0.5) describes a case with low transport costs per distance unit, and these decline only slowly with increasing distance (e.g. because of good roads). In contrast, a high *β* value (Figure 1b *β* = 5) describes a case where even at a small distance transport costs are relatively high and these transport costs increase fast with increasing distance (e.g. because of poor roads between fields). In this case, cost savings resulting from productivity improvements through the use of large machinery and more efficient use of labour can only be achieved when fields are adjacent to each other.

[Figure 1 about here]

If we further assume that all fields have the same level of output (*xm*=*x* for all *m*), then the net benefit of an isolated field is *px*-*a*+*zx*. Without loss of generality we set *px*-*a+zx*=1. Further denoting *zxm*=*w* we obtain

 (3)

 The term *w* can be identified with the weight of the economic interaction between the fields in that it describes the potential scale of benefits that could be obtained by full agglomeration. The net benefits from the agriculture production in the landscape with *N* fields are obtained by summing over all *bm*.

We now assume that the presence of an invasive pest species reduces agricultural profits. Without loss of generality we set the net benefit of an infested field to zero. Denoting the probability of field *m* being infested by *pm*, the expected net benefit of agriculture production in the agricultural holding is

 (4)

To determine the probabilities *pm*, we consider that invasion into a field may occur by dispersal from the surrounding area into the landscape studied or by dispersal between different fields in the agricultural holding. The vectors for dispersal[[1]](#footnote-1) may be wind, water, animals, or human activity (e.g. movement of people, vehicles, materials or equipment) (e.g. Levine and D'Antonio, 2003; Ruíz and Carlton, 2003). While dispersal allows the species to spread in the landscape, due to environmental or demographic factors, a local population on a field can go extinct, so formerly infested fields may become uninfested again. We consider only natural causes of local extinction; control measures that may foster local extinction are ignored in this study.

We formally describe these dynamics of the pest species in the farming landscape with a spatially explicit stochastic metapopulation model (cf. Hanski, 1999). A metapopulation is a set of local populations, each inhabiting a habitat patch in the landscape. The metapopulation approach we have adopted therefore represents a situation in which a potential invasive (which could be either exotic or a naturalised pest) exists in the landscape, but it is less well-suited to the situation of a newly-invading organism. In the model, local populations can go extinct but empty patches can be recolonised. To study effects of habitat patch arrangement on the dynamics of metapopulations it is convenient to abstract from the dynamics within the local populations and consider only whether a field is occupied by the species or not (Hanski, 1999; Frank and Wissel, 1998). Accordingly, we only have to model the transitions on each of the *N* fields between these two states, and the state of the species in the farm determined by the *N*-element vector  with  where *sm*=1 represents a field *m* being infested and *sm*=0 uninfested.

Transitions between infested and uninfested states occur due to three different processes: (1) If *sm*=0, organisms immigrating from the surrounding area outside the *N*-field system establish a local population in the field (changing *sm* to 1) at a rate (probability per time unit) *i*; (2) If *sm*=0, a local population on another field *n* colonises field *m* (changing *sm* to 1) at a rate *cexp(-αdmn),* where *c* is the emigration rate of organisms from the source field *n* and *dmn* is the distance between fields *m* and *n*. The exponential function considers that the probability of emigrating organisms reaching another field declines with increasing distance between the two fields. The rate of this decline, *α*, can be identified with the inverse of the pest species’ mean dispersal range. A higher α (or smaller 1/ α) represents a small ability to disperse to distant plots; (3) If *sm*=1, due to environmental or demographic influences the local population on the field goes extinct (changing *sm* to 0) at rate *e*.

The transitions between different states  of the metapopulation are modelled as a Markov process (e.g., Häggström 2002; cf. Appendix A). We focus on an equilibrium state where the associated probabilities of any of the fields being infested, *pm* are constant in time. The obtained values for *pm* (i.e. *p1* and *p2* in Appendix A for a scenario with two fields) are inserted into the agricultural profit function, eq. (4) as explained below.

**2.2 Model analysis**

We are interested in the optimal spatial allocation of the agricultural fields, measured by the optimal distances *dmn*\* between all pairs (*m*,*n*) of fields, that maximises the agricultural holding net benefit *B*. In a first step we first consider a two-field system and estimate the optimal distance *d*\* between the two fields that maximizes the expected agriculture net benefits *B*. For two fields there are four metapopulation states to consider:  and the probabilities *p*1 and *p*2 of fields 1 and 2 respectively being infested can be determined analytically (see Appendix A). Inserting *p*1 and *p*2 into eq. (4) expresses the expected net benefit as a function of the inter-field distance *d* and the model parameters *i*, *e*, *c*, *w*, ** and **. An analytical solution for the optimal distance *d*\* is not feasible, so we determine it numerically by continuously varying *d* from zero to very large numbers and identifying the value that maximizes the agricultural holding net profits, *B,* and exploring how the optimal *d* depends on model parameters. In a second part of the analysis, we consider a system of 5 by 5 fields that are arranged on a square grid[[2]](#footnote-2). The infestation probabilities *pn* (*n*=1,…,25) are obtained through numerical simulation. For this we simulate the processes of immigration, local extinction and recolonization for 10,000 time steps and count the proportion of time steps for which a given field *n* is infested. The resulting *pn* are then inserted into eq. (4) to obtain the expected net benefit *B*. As in the two fields scenario, we numerically determine the optimal distance *d*\* for different cases[[3]](#footnote-3).

**3.- Results**

**3.1.- Results for the 2-fields landscape**

The probability of field 1 (2) being infested is (Appendix A)

 (5)

Inserting eq. (5) into eq. (4), the expected net benefit in the 2-field landscape becomes

 with (6)

 (7)

with the first order necessary condition given in the Appendix. Since in eq. (6) *k* is the multiplier of *exp(*-*αd*), we denote this term as the weight of the ecological interaction (analogous to the denotation of *w* as the weight of the economic interaction). This weight can be interpreted as the influence of pest pressure on farmer/manager decisions.

For a large number of model parameter combinations we maximise the net benefits (eq. 6) controlling for the distance, *d*, between the two agricultural fields. Results can be summarized attending to two cases:

*Case 1*: Efficiency gains by clustering fields decline fast with increasing distance between them (case A, fig. 1), and *the distance at which the fields should be located to allow for savings in costs is smaller than the distance at which the invader is able to disperse* (*i.e.* *β* > *α* or 1/ *β* < 1/ *α*)

In this case, there exist only extreme solutions with all choices however leading to poor expected benefits.

* In situations where the potential savings in costs from field clustering through a more efficient use of inputs is smaller than the potential to have losses due to infestation if nothing is done (i.e., *k*>*w*) the benefit is maximised by an infinite distance, *d*\*→∞ (fig. 2c).
* If the potential savings in costs from field clustering through a more efficient use of inputs is higher than the potential to suffer losses due to infestation (i.e., *k*<*w)* the benefit is maximised by a zero distance and for *k*=*w* it is maximised by zero or infinite distance (fig. 2c).

To understand the reason for these extreme results consider that the expected net benefit depends on a distance between fields that fulfils two sub-objectives: production efficiency (cf. eq. (3)) must be sufficiently high and the probability of infestation (eq. (5)) must be sufficiently low. Therefore, if the distances at which the two fields need to be located to generate cost savings through efficiency gains is such that the pest invader can easily disperse between fields, then it is impossible to accommodate both objectives at the same time and no reasonable finite compromise distance *d*\* can be found. Instead, if the weight of the ecological interaction (*k*) is larger than that of the economic interaction (*w*) the optimal distance is infinite to minimise the probability of infestation; if the weight of the economic interaction is larger than that of the ecological interaction the optimal distance is zero to maximise production efficiency; and if both weights are equal both options lead to equal results. The same is observed if the economic and ecological distance interactions are similar, **=** (fig. 2b).

[Figure 2 about here]

*Case 2*: Efficiency gains by clustering fields decline slowly with increasing distances between them (case B, fig. 1), and *the distance at which the fields should be located to allow for savings in costs is larger than the distance at which the invader is able to disperse* (i.e. **<** or**1/** >1/**)

In this case, it is possible to find a finite compromise distance that leads to reasonably high production efficiency and reasonably low probability of infestation. Figure 2a shows that this optimal distance decreases with increasing potential savings in costs through a more efficient use of inputs (*w*). This means, the higher the scope for economies of scale, the smaller the distance between the two fields.

In addition, note that optimal distance *d\** increases with increasing weight of the invasion probability in the farmer’s decision (*k*). In addition, using eq. (7), results show that the optimal distance increases with theprobability of colonisation (*c*), decreases with the rate of extinction (*e*) and exhibits a maximum with respect to probability that a pest from any area outside the farm infects the fields (*i*)*.* While the effects of *c* and *e* are obviously plausible, the non-monotonous effect of *i* needs some explanation. At very small probability of infestation through the surrounding landscape (*i),* this probability can be ignored so that a small distance should be chosen to improve production efficiency, while at very large probability of infestation (*i)* establishment of the invader cannot be avoided independent of the distance between fields (*d)*, so again it is optimal to ignore the invasion altogether and choose a small distance. Only at medium levels of *i* is it sensible to consider the probability of infestation and choose a larger distance (figure 6 illustrates these results).

Figure 3 provides a further exploration of the optimal distance for this case 2. One can evaluate situations where *1/ >> 1/*, i.e., when the distance at which the fields should be located to allow for savings in costs is much larger than distance at which the invader is able to disperse. Here and henceforth in the paper the symbol “>>” and the term “much larger” mean “larger by at least an order of magnitude”. For the symbol “<<” and the term “much smaller” the equivalent applies. In those cases, the optimal distance *d*\* increases with increasing ability to disperse 1/** (panel b), and decreases with increasing ** (panel a). This is intuitive, since the shorter the distance at which the fields need to be located to have some gains in efficiency, the shorter is the optimal distance.

[Figure 3 about here]

Moreover, figure 3 also shows, consistently with the results from case 1 above, that as the ratio **/** approaches 1 (i.e. the economic spatial interaction of the fields is similar to the ecological interaction), the optimal distance is either zero or infinite, depending on the values of *w* and *k* (panel a and b). For *w*<<*k[[4]](#footnote-4)* (i.e., where savings in costs through a more efficient use of inputs is much smaller than the possible losses due to infestation if nothing is done) the optimal distance *d*\* sharply increases. Otherwise the optimal distance *d*\* becomes zero, implying that full clustering is optimal.

**3.2 Results for the 25-fields landscape**

 The analysis of the 25-fields landscape leads to the same qualitative results as that of the 2-fields landscape[[5]](#footnote-5). Figure 3 shows the optimal distance *d*\* as a function of the two interaction lengths 1/** (higher 1/** implies higher invader dispersal ability) and 1/**(higher 1/** implies that the larger the distance between fields at which is possible to exploit economies of scale). One can evaluate similar cases as those explored in the previous section.

 *For case 1* (as described above)*,* results are illustrated inlower right halves of figures 4a and 4b, and they showthat optimal distance is either *d*\*=0 or *d*\*→∞ **depending on whether *w*/*k*>>1 or *w*/*k*<<1, respectively; i.e., it depends on the relation between the potential savings in costs and the weight given to losses if an infestation occurs. This outcome agrees with the results for case 1 for the 2-fields case.

*For case 2* (as described above)*,* results are illustrated in the upper left halves of the figures 4a and 4b, and the negative slopes of the isolines indicate that optimal distance *d*\* increases with increasing dispersal range of the species (1/** and increasing 1/** (i.e. distance between fields at which is possible to exploit economies of scale), which again agrees with the 2-fields result describe above.

Moreover, figures 5 and 6 show *d*\* as a function of *c*, *e* and *i*. As argued in the previous section, *d*\* increases with increasing *c* and decreasing *e* (increasing slopes of the isolines in Fig. 5); it exhibits a maximum[[6]](#footnote-6) as a function of the probability of infestation from the area outside the farm (*i).*

One may ask whether a clustered or a scattered configuration of the fields is better in terms of the net benefit *B*. The general rules that apply are shown in Table 1.

Table 1. General rules regarding the optimal distances for field clustering in relation to input costs, the dispersal characteristics of the invader and the probability of invasion occurring

|  |  |
| --- | --- |
| Case Description | Optimal distance |
| If distance at which the fields should be located to allow for savings in costs is smaller than distance at which the invader is able to disperse | If the agglomeration forces in terms of cost savings that could be obtained by fields’ agglomeration is higher than the farmer’s weight to the probability of having a pest infestation problem | Clustering*d*\*<<1/** |
| If the agglomeration forces in terms of cost savings that could be obtained by fields’ agglomeration is smaller than the weight given by the farmer to the probability of having a pest infestation problem | Scatteringd\*>>1/ |
| If distance at which the fields should be located to allow for savings in costs is much larger than distance at which the invader is able to disperse | Optimal distance[[7]](#footnote-7) is higher than invasive’s dispersal range; but small enough for allowing for some savings in costs through economies of scale1/**<<*d*\*<<1/** |
| If distance at which the fields should be located to allow for savings in costs is slightly larger than distance at which the invader is able to disperse | Optimal distance is of the order of the invasion range (1/**) and economic interaction distance (1/** |

**Discussion and Conclusions**

Fragmented landholdings constrain efficient agricultural cultivation. Therefore, landscape management and re-allotment of agricultural parcels was and still continues to be an important instrument to improve business structure in rural areas in many countries (e.g. Robinson and Sutherland 2002; Vitikainen 2004; Thomas 2006). In this paper we have analysed this policy of spatial concentration of agricultural crops where there is the probability of pest invaders. The model consists of an agricultural area with *N* fields, and producers have their fields distributed in the landscape. For each farmer, labour will be more productive if there is a high concentration of fields at nearby locations. In addition, transportation of machinery is costly, and this cost increases with distance, and poor road conditions. Therefore, these costs of the agricultural activity act as a centripetal force to concentrate crop production. However, if owners’ management units are concentrated, the probability of spread of invasive species across their fields will be higher, and they would be faced with damages and control costs of the invasion. The probability of spread of invaders acts as centrifugal force, arguing for a more dispersed spatial allocation of the fields and questioning aggregation policies. We studied the optimal distance (level of concentration) between agricultural fields, given the trade-offs between these centripetal and centrifugal forces.

The results of our analysis are the following. (a) When agricultural productivity decreases rapidly with increasing distances between the fields and the dispersal ability of the invader is high, then no compromise distance can be found in the model and the optimal distance is either zero (if economic productivity is considered more important for economic net benefits than the probability of an infestation) or infinite (if economic productivity is considered less important for economic net benefits than the probability of an infestation). (b) If, on the contrary, the invaders’ ability to disperse long distances is small compared to the range of the economic interaction, a moderate “compromise” distance between the fields exists which is relatively large (small) when the weight given to economic productivity is large (small) compared to the weight given to the probability of infestation. This optimal distance is positively related to the probability of spread of the invasion from a nearby field, and negatively related to the probability that local populations of the invader will go extinct due to environmental or demographic factors. Interestingly, the optimal distance has a maximum at medium levels of the rate of invasion from the surrounding landscape. This is because if this rate is very low, it can be ignored in farmers’ decisions, and if it is very large, then invasion is inevitable, and then farmers’ can be better to choose very small distances attending purely to economies of scale. (c) We can also conclude that in general the optimal distance is largely positively related to both the economic and ecological interaction range. Thus, it is optimal to have greater distances between the fields if agricultural productivity declines slowly with increasing distance and if the dispersal range of the potential invader is high.

 This analysis has evaluated preventive policies by focusing on the spatial arrangement of an agricultural landscape to reduce the probability of spread of invaders. However, institutional aspects such as the size of farm holdings, although related to this study, have been ignored. The increase in size of farms has further implications for managing the risks of invasion, since the incentive of each farm owner to control is affected by the probability of reinvasion from uncontrolled neighbouring infestations. Therefore the smaller the size of each holding within the invasive’s potential range, the higher the number of agents involved. In those circumstances, the need for incentives and institutions in shaping a coordinated response to invasions (Epanchin-Niell et al., 2010; Epanchin-Niell and Wilen 2014), and an understanding on the social dissemination of control strategies (Rebaudo and Dangles, 2013; Carrasco et al. 2012) is key for successful pest management. Nevertheless, our results reinforce the existing literature on the creation of barrier zones along the growing edge of an invasion (Sharov and Liebhold 1998; Sharov 2004) where those zones consist of unsuitable habitats for invasive species establishment. Potapov and Lewis (2008) show that if the landscape has clusters of highly connected invasible habitats, once several patches in a cluster are invaded, it is optimal to allocate resources to prevent the spread to other clusters. The spatial allocation of non-susceptible habitats (barrier zones) to limit the invasion spread across the landscape can be interpreted as similar to the interspersion of fallow fields between croplands studied here.

The landscape approach taken in this paper fits in well with current thinking about obtaining greater environmental gains from the management of the agricultural landscape (e.g. Di Falco et al., 2010; Kremen and Miles 2012; Steward et al. 2014). Pretty (1997) was one of the earlier adopters of the sustainable intensification concept which relies on the ‘‘integrated use of a wide range of technologies to manage pests, nutrients, soil and water”. The outline agreement of reforms to the EU Common Agricultural Policy (CAP) post 2014 include greening measures such as crop diversification, ecological set-aside, and preservation of permanent grassland and green cover. The crop diversification measure, aimed at improving the resilience of soil and ecosystems, might also be expected to, at the margin, increase the distance between fields of the same crop and thus potentially reduce pest pressure depending on the spread characteristics. Recent reviews of UK biodiversity conservation have emphasised the need to adopt a more integrated landscape-scale approach (e.g. Lawton et al, 2010), and this is now emphasized in policy documents as well (e.g. Defra 2011). Our analysis has demonstrated the importance of landscape-scale considerations in determining optimal farm management to prevent invasions of pests or disease. However, it has also highlighted the complex and potentially conflicting pressures on farmer decisions caused by interactions between ecological and economic factors at the landscape scale. More effective use of landscape-based strategies to reduce the probability of invasive species depends on a better understanding of the nature of these interactions, and how they vary in relation to different farming systems and dispersal characteristics of invasive species and pathogens.

**Appendix A: Calculation of the probability of a field being occupied by the pest species**

The metapopulation dynamics is modelled as a Markov process for a 2-field system. We denote as *p*00, *p*10, *p*01 and *p*11 the probabilities of both fields being empty (not occupied by the pest species), respectively field 1 being occupied and field 2 being empty, respectively field 1 being empty and field 2 being occupied, respectively both fields being occupied. Assuming that only one transition can occur at a given point in time, these probabilities change in time via

 (A1)

Considering, e.g., the first equation, the first term on the r.h.s. considers colonisation of field 1 or field 2 from outside the system and the second term the extinction of a population on field 1 respectively 2. The middle term, on the r.h.s. of the second equation, considers colonisation of field 2 from outside, extinction of the population on field 1, and colonisation of field 2 by emigrants from field 1.

We are interested in the steady state,  of the system, which is obtained with some algebra as

 (A2)

The probability of field 1 respectively field 2 being occupied by the pest species is , respectively . Inserting eq. (A2) delivers eq. (3).

For *N*=3 or more fields the steady state cannot be determined analytically. Instead the metapopulation dynamics on the fields is simulated. For this we form all possible states from *p*00…0 to *p*11…1 where each index refers to one of the fields and is 0 if the field is empty and 1 if it is occupied by the pest species. The transitions between all 2*N* states are determined analogously to eq. (A1), leading a set of to 2*N* differential equation *dp*…/*dt*=… Each equation is discretised with respect to time by replacing *dp*/*dt* by [*p*(*t*+*t*)-p(*t*)]/*t* with sufficiently small time interval *t*. For eq. (A1), e.g., one would obtain

 (A3)

Starting from the (without loss of generality) initial condition *p*00…0(t=0)=1 and zero probability for all other states, we determine the probabilities *p*(*t*) for all states, insert these probabilities into the equation system to determine the probabilities for time *t*=2*t*, and so on, until the unique steady state is reached where the probabilities do not change any more. The probability of observing field *i* occupied then is the sum the probabilities of all states in which field *i* is occupied.

Inserting these probabilities into eq. (4) leads to eq. (6) for two fields. The first order necessary condition is given by



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Figure 1: Average cost of production for one of two fields which have a distance of *dn*,*m*. Constant *z*=1.



Figure 2: Optimal distance *d*\* (shown by colour scale) as a function of the ecological (*k*) and economic (*w*) interaction weights for different values of **/**. The interaction weights are on logarithmic scale; the optimal distance is scaled in units of the range of the ecological interaction (1/).

|  |  |  |
| --- | --- | --- |
| (a) | (b) | (c) |
|  |

Figure 3: Optimal distance *d\** as a function of the ranges of the ecological (1/) and economic (1/) interactions for various levels of interaction weights *w* and *k*. In panel a the optimal distance, *d\*,* and *1/* are scaled in units of *1/* which is kept constant. In panel b the optimal distance, *d\*,* and *1/* are scaled in units of *1/* which is kept constant.

|  |  |
| --- | --- |
| (a) | (b) |
| Macintosh HD:Users:JuliaTouza:Documents:PAPERS:Food Security-2010-15:dreschleretal2015fig3.png |

Figure 4: Optimal distance *d*\* as a function of 1/** and 1/**. The optimal distance is shown by colour scale. All distances, 1/**, 1/** and *d*\* are scaled logarithmically.

1. *w*/*k*>>1



b*w*/*k*<<1



Figure 5: Optimal distance *d*\* as a function of *c* and *e*.



Figure 6: Optimal distance *d*\* as a function of *i*



1. Dispersal vectors may have quite different relationships with the adjacency of farms. For a disease agent that depends on animals or human-caused transfer, adjacency may be critical. But for water- or wind-borne agents, immediate adjacency is less likely to be critical in determining spread (it will still be related, but potentially less strongly). [↑](#footnote-ref-1)
2. The distance between adjacent fields is *d*/2 so the length and width of the whole grid is 2*d* and the average distance between two randomly chosen fields is about *d.* [↑](#footnote-ref-2)
3. The optimal distance was evaluated attending to the dispersal ability captured in ** and potentials for economics of scale through aggregating captured in ** for the following two parameter combinations: *c*=0.8, *e*=0.1, *i*=0.01, *w*=10 (*w*/*k*=15) and *c*=8, *e*=0.1, *i*=0.01, *w*=0.1 (*w*/*k*=0.15). We further determine *d*\* as a function of *c*, *e* and *i* for 1/**=20 and 1/**=100 [↑](#footnote-ref-3)
4. This situation is illustrated in figure 3, for example as w=1 k=10; or w=0.1 k=1 [↑](#footnote-ref-4)
5. The same is found for a landscape with 3 by 3 fields (not shown). [↑](#footnote-ref-5)
6. Maximum that occurs around *i*=*e.* [↑](#footnote-ref-6)
7. In this case, *d*\*>>1/** (Fig. 3a) and *d*\*<<1/** (Fig. 3b), which means **>>1/**

 and 1/**<<*d*\*<<1/** [↑](#footnote-ref-7)