Ecological network analysis: an application to the evaluation of effects of pesticide use in an agricultural environment

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Abstract: Ecological network analysis is used to evaluate the impact of pesticide use on ecological systems in the context of agricultural farmland environments. The aim is to provide support for the design of effective and minimally damaging pest control strategies. The ecological network analysis can identify species that are important to the integrity of the ecological network. The methodology can be used to monitor the impact of shifts in terms of types of pesticide used on the ecological system. The authors’ intention is to use this methodology to provide supporting evidence for the UK Voluntary Initiative programme aimed at convincing farmers voluntarily to make improved choices in the use of a wide range of pesticides.

Keywords: ecological systems; impact analysis; network analysis; pesticides

1 INTRODUCTION

Pesticides have been used at industrial scale since the early twentieth century. The benefits of pesticide use for industrial-scale agriculture include much increased efficiency in land use, massively increased crop productivity and significant financial benefits. Major side effects of large-scale pesticide use include reduction in the diversity of flora and fauna in the area of application, accumulation of pesticide-related substances in the soil and groundwater and possibly the emergence of pesticide-resistant pest species. Contemporary agricultural science recognises that abusive use of pesticides cannot lead to sustainable agricultural practices in the long term.1 Consequently, the development of pesticide use practices compatible with sustainable agriculture represents a key issue in the context of current agricultural policies.

In recent years, the Voluntary Initiative (VI) programme has been initiated,2 which aims to persuade farmers of the advantages of improving their use of pesticides. An important aspect of the programme is to develop effective and efficient methods to measure the impact and effect of pesticide use on ecological systems. Having such methods can help in producing convincing evidence about the design of sustainable agricultural practices.

Ecological systems consist of a large number of species, linked together by interactions between them, and further environmental factors (e.g. wind, humidity) that contribute to the determination of the dynamics of the ecological system.3 Examples of such species interactions are predator–prey interactions (i.e. one species acts as a food source for another species), competitive interactions (i.e. two species compete for the same natural resource) and supportive interactions (i.e. byproducts of one species constitute a resource for another species). The evolution of ecological systems follows very complex patterns requiring appropriate simplified models to make the analysis of such systems possible.

Early models used differential equations (e.g. Lotka–Volterra equations) to describe the quantitative ecology of interacting species.4 Such models can deal efficiently with a relatively small number of species. As the number of species increases, the analysis of such coupled differential equation systems becomes extremely difficult in computational terms. Existing modelling tools such as the NETWRK can help in handling a relatively large number of coupled equations organised into a network.5 Note that mean field models can deal even with very large systems of coupled equations, but they lead to averaged solutions,
ignoring practically important individual differences between species. A recent approach to dealing with large-scale complex systems such as ecological systems is to use graph theoretical network models of such systems. Such network analysis has been applied primarily to structural analysis of food webs. These studies established that many such ecological networks are scale-free networks, but those of small size and with dense interconnections between participating species do not belong to this common class of naturally arising networks. Recent work on various species indicates that structurally important components of the graph representation of the system are also functionally important in the context of the real system. This observation has been used recently to point out vulnerabilities in natural systems and to measure the severity of damage in natural systems. The present authors follow the graph theoretical network analysis approach in modelling and analysing ecological systems. The aim is to develop an analysis tool for ecological systems that can be used to evaluate the damaging effects of pesticide use on the analysed ecological system. This tool can be used to evaluate scenarios of pesticide use in the context of farmland environments and to provide objective support for rational decision-making about balanced pesticide use policies that minimise the damaging impact on the ecological system while maintaining the desired levels of productivity.

Data from the Boxworth project were used to construct a model of a farmland ecological system. The present ecological system representation includes nodes and interactions for many plant and animal species and also for major environmental factors. Data about the direct effects of pesticides on pest species were also considered. Well-established network analysis methods were used to evaluate the structural importance of nodes and interactions within the network representation of the ecological system. This analysis provides the basis for evaluation of the structural importance of the damage caused by the application of pesticides. In accordance with the assumption concerning the correlation between the structural and functional importance of network components, the measure of the structural damage caused by the application of pesticides also provides a proxy measure of the functional damage that is likely to be caused by application of pesticides to the ecological system. The methodology is demonstrated in the context of the analysis of a winter wheat farmland environment. It is shown how to use the proposed network analysis methods to evaluate the likely damage caused by different pesticide use scenarios to the ecological system selected. The results indicate that the present ecological network analysis can be applied to support rational decision-making about pesticide use policies. The authors’ analysis has the potential to open up new perspectives for ecologically safe agriculture. While traditional pest control approaches concentrate on single targets, possibly combining such single-target strategies, the network analysis approach makes it possible to design effective multitarget strategies with much less secondary damaging effects than focused single-target methods.

The rest of this paper is structured as follows. Section 2 describes key graph theoretical concepts, the data used, the conceptual framework of the methodology and the main steps in developing the analysis tool. Section 3 describes the application of the proposed network analysis methodology and the results in the context of the ecological system selected (winter wheat farmland). Finally, Section 4 contains a discussion of the results and the conclusions of the paper.

2 METHODS AND MATERIALS
2.1 Fundamental concepts
A graph \( G = (V, E) \) consisting of a finite set \( V \neq \emptyset \) and a set \( E \) of two-element subsets of \( V \). The elements are called vertices or nodes. An element \( e = \{a, b\} \) of \( E \) is called an edge with end vertices \( a \) and \( b \). An example of a graph is shown in Fig. 1(a). In a graph representation of an ecological system, nodes represent species, pesticides and other environmental factors, and edges represent the interaction between them (note that these interactions can be of various nature, e.g. interactions between predator and prey, interactions representing competition or cooperation.

![Figure 1. A graph: nodes are the numbered round dots, edges are the segments linking the nodes.](image-url)
etc.). Graphs may be directed or undirected. In directed graphs, edges have a direction (i.e. from one node to another), and in this case directed edges are called arcs. In undirected graphs, edges have no direction. Naturally, directed graphs are more appropriate for representing systems in which the direction of interaction is important (e.g. members of one species eat members of another species), while undirected graphs work better if the interactions have no specific direction (e.g. symbiotic interactions between two species – of course, this could also be seen as a pair of directed arcs between nodes representing the two species).

A graph can be represented by its adjacency matrix. A graph $G$ with vertex set $\{1, \ldots, n\}$ can be specified by the $n \times n$ matrix $A = (a_{ij})$, where $a_{ij} = 1$ and $a_{ji} = 1$ if there is an edge from node $i$ to $j$, otherwise the entry is 0 (in the case of directed graphs, $a_{ij} = 1$ if there is an arc from node $i$ to $j$, otherwise its value is 0).

Connectivity measures of a network express the level of integration of information processing within the system represented by the network. Network connectivity measures include the average clustering coefficient, the isolated node ratio and the average minimum path length. These measures are typical measures used in the literature. Network connectivity measures can be used to evaluate the preservation of system integrity after damage suffered by the system. The damage to the system can be represented as loss of nodes or connections between nodes [see Fig. 1(b)]. Measuring and comparing network connectivity measures calculated for the intact and damaged networks allows the calculation of a measure of the loss of structural integrity of the system. Following the assumption concerning the correlation between structural integrity of the graph representation of a system and the functional integrity of the system that is represented by the graph, the measure of the loss of structural integrity can be interpreted as a proxy measure of the loss of functionality of the real system represented by the network model.

The minimum path length between two nodes $i$ and $j$ is the smallest number of edges that need to be traversed to go from node $i$ to node $j$. Given two nodes $p_i, p_j \in V$, let $l_{ij}$ be the length of the shortest path connecting these two nodes, following the connections present in the network. The average path length $l_{ave}$ is defined for connected parts of the network as

$$l_{ij} = \frac{2}{n(n-1)} \sum_{i<j} l_{ij}$$

A small $l_{ij}$ is essential for the rapid and efficient integration of information flow between nodes $i$ and $j$. In the simplified graph in Fig. 2(a), the average path length is $l_{ave} = 1.9$ and, after knocking out one node, it increases to $l_{ave} = 2.13$ [Fig. 2(b)].

The isolated node ratio (ISR) is the ratio between the number of isolated nodes and the total number of nodes present in the network. In Fig. 2 the ISR is zero because there are no isolated nodes. The presence of many isolated nodes (i.e. high ISR) indicates the disconnected segmentation of the original connected network, and implies reduced informational integration of the system represented by the network graph.

Let $\Gamma_i = \{p | a_{ij} = 1\}$ be the set nearest neighbours of a node $p_i \in V$. The clustering coefficient $C$ of a node $p_i$ is defined as the ratio between the actual number of connections between the nodes $p_j \in \Gamma_i$ and the total possible number of connections $k_i(k_i - 1)/2$, where $k_i = |\Gamma_i|$:

$$C(p_i) = \frac{2}{k_i(k_i - 1)} \sum_{j \in \Gamma_i} \sum_{k \in \Gamma_i, k > j} a_{jk}$$

The average clustering coefficient is defined as the average of $C(p_i)$ over all the nodes in a given network:

$$C_{ave} = \frac{1}{n} \sum_{i} C(p_i)$$

A high $C_{ave}$ is important for the functionality of the network, as it expresses the integration of the functional interaction clusters. In Fig. 2 the average clustering coefficient decreased from $C_{ave} = 0.33$ to zero after knocking out one node.

The connectivity measures reflect the changes to the network after knocking out some nodes (for example, in the case of ecosystem representations, the application of pesticides can be represented by knocking out some nodes). If a knocked-out node is a highly connected node, e.g. nodes 4, 8 and 13 in Fig. 1(a), then their removal from the network has a high impact on the integrity of the network. This is illustrated in Fig. 1(b) where node 13 was removed from the network, leaving several nodes isolated.

Note that it is possible to define further network connectivity measures, and having more complete measures benefits the integrity analysis. Other more complete measures can be constructed by considering, for example, eigenvalues and eigenvectors of matrices representing the graph.

2.2 Data collection

Winter wheat fields were chosen as a typical farmland environment for analysis. The decision was made primarily because of the amount of relevant information available and also because wheat production is one of the major farming practices in Britain today. The data about species and their

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**Figure 2.** Illustration of integrity measure change; $l$ is the length; ISR is the isolation node ratio; $C_{ave}$ is the average clustering coefficient.
interactions were taken to a large extent from the Boxworth project report.17 This project measured the use of pesticides on crop fields on a practical scale. The data from the Boxworth project provided a large list of plant and animal species in addition to other useful information. The species list provided by the Boxworth project has been updated and consolidated, and constitutes the nodes of the present ecological network model. Additional data were also obtained from a literature search,20–27 the Internet and personal communications with relevant experts from the School of Biology, University of Newcastle upon Tyne. Note that, as further data become available, containing more detailed information about interactions between species, these data can be added to the existing data in order to increase the quality of the database. Potential sources of additional data include studies on the effects of herbicides on biodiversity and evaluation reports published by PSD for individual compounds.28 In general, the Boxworth data are sufficiently good to prove the concept behind the ecological network analysis methodology.

The node list of the ecological network model has, in addition to plant and animal species, other factors associated with a biological network such as soil types, weather conditions, fertilisers and diseases. All these factors are to be taken into account when examining the effect of pesticide impact on the network. Owing to different levels of information about nodes, it was decided to design a simple network. Thus, some data were simplified, for example, the growth of winter wheat was considered in four stages represented by the four seasons. This was also the case for modelling of weather conditions: temperature, sunshine, rainfall and wind force (classified as maximal, average and minimal).

The ecological system of a winter wheat field and its neighbouring hedges comprises nodes as listed in the Appendix (all data that were used are made available as part of the supplementary information; see ‘Supplementary material’, immediately before the Acknowlegements section). The network model contains 184 nodes comprising 118 species, 43 diseases and 23 other factors. The species include birds, mammals, spiders, mites, molluscs, earthworms, insects (such as beetles, ladybirds, flies, moths, bees, midges, leafhoppers, aphids, thrips and springtails) and plants (ranging from trees and shrubs to herbs and weeds). In addition, for the impact of pesticides on the ecological system, 82 pesticides (comprising 61 active ingredients) are used (see supplementary information). The pesticides include bird repellents, dessicants, fungicides, growth regulators, herbicides, insecticides and molluscicides.

After generation of the node list, the next step was to formulate links between related nodes. The links among the nodes are represented by an $n \times n$ adjacency matrix, where $n$ is the number of nodes. Owing to the lack of detailed and reliable information about interactions between species and between species and other environmental factors, it was decided to use qualitative labels as values of the entries of the adjacency matrix. Firstly, the value of an entry representing the link between nodes $i$ and $j$ is set at 1 if there is an interaction between the species/environmental factors represented by these nodes. Otherwise the value of the matrix entries is set at 0. In addition, + or − signs are added to the links represented by 1, expressing the nature of the link. A link from $A$ to $B$ is given the value +1 if the presence of species/environmental factor $A$ facilitates the presence of species/environmental factor $B$. If the opposite is the case, the value is set at −1. For example, if $A$ consumes $B$, then there exists a link from $A$ to $B$ weighted with +1 and there also exists a link from $B$ to $A$ weighted with −1, to denote that $B$ is eaten by $A$. In Fig. 3 an ecological system is presented schematically, where arrows are used for simplicity. The +1 weighted link is denoted by the direction of the arrow, and the −1 weighted link by the opposite direction, e.g. a bird feeds on an insect and an insect is consumed by a bird.

To describe the changes in the development of the ecological system, four interaction matrices were prepared, to reflect the four seasons. These matrices were stored in the model database. The database has several tables, including information regarding the individual nodes, the interaction of nodes for each season, the environmental factors, the soil classification and the pesticides, including the list of network nodes that they knock out.

2.3 Methodology
The approach to analyse the impact of a pesticide on the ecological system is illustrated in Fig. 4. Firstly, the network is updated by selecting the environmental factors such as weather conditions, soil type and fertiliser. Also, wheat diseases and applied pesticide are added to the network. During this process the network is visualised so that the user is able to view node information. Either a manual analysis or a minimal impact analysis is performed to determine the damage to the network.

The impact of the pesticide on the ecological system is modelled as follows. Nodes that are affected directly by the pesticide are removed from the network. The indirect effects are determined by considering the impact of the nodes that have been removed, i.e. if
the existence of a node depends critically on removed nodes, this node is also removed (isolated nodes are removed only if their existence depends on other nodes that were removed as an effect of pesticide application). The existence of a node $A$ depends critically on the existence of other nodes forming a set $S$, if more than half of the facilitating nodes of the node $A$ are part of the set $S$. Note that in real ecosystems the effects of pesticides are more likely to be gradual, and possibly only in the long term may they lead to complete or near-complete elimination of species. However, for the sake of simplicity, and to maintain the applicability of the present methods based on graph theory, an appropriate abstraction was adopted in terms of the removal of nodes as the effect of pesticide application.

The impact of the use of pesticides is evaluated using the previously described graph integrity measures. To evaluate the effect of the damage, the effects are compared with the average expected damage caused by random removal of a single node and possible affected nodes from the network (the removal of a node may imply the removal of further nodes that may depend on it). The average damage and the variance of the damage in the case of random node removal are calculated, and these values are used through the $u$-test to calculate whether the damage caused by application of a pesticide is statistically significant or not (i.e. is the actual damage significantly different from the average expected damage or not). Supposing that $\bar{x}$ is the average damage measure, $\sigma$ is the variance of the damage measures calculated for random node removal and $x$ is the damage caused by application of a pesticide, the $u$-value is calculated by means of the equation

$$ u = \sqrt{n} \cdot \frac{x - \bar{x}}{\sigma} $$

where $n$ is the number of random node removals considered for the calculation of $\bar{x}$ and $\sigma$. If the absolute magnitude of the $u$-value is above 1.96 the difference is significant (the likelihood that the two measured values are the same is less than $P = 0.05$), and if it is above 2.57 the difference is very significant (the likelihood that the two measured values are the same is less than $P = 0.01$). If the difference between the actual damage and the expected average damage is significant, it is considered that the ecological damage caused by the application of the pesticide is significant. If the damage caused by application of pesticides is not significantly different from the damage caused by random node removal, this indicates that the application of these pesticides may not do very much harm to the integrity of the ecosystem (i.e. the expected caused damage is comparable with the damage that might be caused by minimal random damage – that of the removal of a single node).

The $u$-value is calculated for all the measures of system integrity described in Section 2. If the damage is calculated to be significant according to more than one ecological integrity measure, then the damage caused by pesticide application can be considered more significant. Considering that the present integrity measures are based on single relevant features of graphs, and none of them offers a comprehensive measure of the change in graph integrity, the authors believe that these measures should be used together in a complementary manner. The conclusions that are drawn in terms of damage caused to the ecosystem are based on a semi-quantitative analysis (i.e. the network and pesticide effects are specified in rather qualitative and abstract terms, while the network analysis is done in quantitative terms) and should be interpreted as a qualitative conclusion based on partly quantitative analysis. This is in line with the assumption concerning the complementary nature of the present damage measures, which does not imply necessarily that they are equally important, rather it means that, considering the uncertainties built into the ecosystem model, it is safer to conclude that the application of some pesticides is significantly damaging if this is indicated by more than one integrity preservation measure.

The two analysis approaches, manual and minimal impact analysis, apply the above strategy. The analysis starts in autumn when winter wheat is sown and is in its early development stage. The process is then repeated for the remaining seasons. In the first approach, pesticides can be manually chosen to exhibit those impacts on the network. Alternatively, the pesticide with the least impact can be determined from different sets of pesticides and their combinations. In this case the graph statistical analysis is applied for all the possible applicable pesticides, and those results are ranked in ascending order with respect to the average minimal path length.
2.4 Tool development
A software tool was developed for the pesticide impact analysis of the ecological system. The software components are illustrated in Fig. 5. From a Microsoft Access database, data of an ecological system are obtained to create lists of network nodes and their interactions that are used by the software tool. The visualisation of an ecological network requires data calculation for the representation of the network. The network statistical analysis is performed by the program 'ecolyser' which requires the interaction list and the pesticide knockout list if the minimal impact analysis is selected. The results of the statistical analysis are stored in a file and are displayed by the software tool.

The database includes all the data that are needed for the pesticide impact analysis. It contains the species list and the interaction list for each season. In addition, a list of diseases, a list of weather conditions, the soil types and the fertilisers are also included. The interactions of nodes are imported from the matrix representation.

The network statistical analyser 'ecolyser' is written in C++. It can be executed with one parameter, an input text file, containing the number of interactions, the number of nodes and the list of interactions between nodes. For the minimal impact analysis, an additional input file is required with information on the potential pesticides that can be applied for a certain pest. It contains the number of pesticides used and a list of the pesticide names, followed by the set of nodes that are knocked out by the given pesticide.

The ecolyser produces an output text file containing the result of the analysis. These results are also displayed on the interface. The user interface consists of an input form and an interaction form, which are shown in Fig. 6. The former allows the selection of a database containing data and properties of an ecological system. The properties include weather conditions for each season, the soil type, fertilisers used and diseases of a crop. The latter visualises the network and represents the results.

3 APPLIED NETWORK ANALYSIS
The pesticide impact analysis of the ecological system is presented in this section. The ecological network of winter wheat fields for each season is illustrated in Fig. 7. It consists of 116 nodes in autumn and winter, and 119 nodes in spring and summer.

During the process of pesticide impact analysis of the ecological system, the network can be visualised in different ways. One way is to zoom in or out and to rotate the network in order to view the structure of the network. Moreover, nodes can be highlighted in two ways: by clicking on the nodes themselves, or by selecting them in the interaction form. In the former case, a small window containing information about the node (node ID, Latin name, common name and category) pops up. In the latter case, after selecting nodes from the list provided, the labels of the selected nodes appear in the network. The visualisation of the node 'slug' is illustrated in Fig. 8.

A pesticide can be introduced to the network by selecting a particular pesticide from the pesticide list and proceeding with the application of it to the network (i.e. elimination of directly and indirectly affected nodes).

Below, the minimal impact analysis that can be performed using the present ecological network analysis tool is described. The first step is to select the environment, using the input screen as
Ecological network analysis of effects of pesticide use

Figure 7. Ecological network of winter wheat.

Figure 8. Visualisation of the node ‘slug’.

shown in Fig. 6(a). This screen is used to select the climatic conditions, soil type and any pests or diseases present in the initial network. Following the selection of input parameters, the relevant network is generated.

After calculation of the network, the season is selected using the dropdown menu at the top of the network display screen. The tool displays the selected network along with the integrity measures for the network before any pesticide is applied.
To see the pesticides that are effective against a particular organism, the node of interest is selected from the node list. For example, by selecting the Aphid as pest, the current database indicates the insecticides Aphox, Dimethoate 40, Dursban 4, Hostathion and Spannit as active agents against aphids.

The effect of applying different pesticides and combinations of pesticides can be examined. The pesticide of interest is selected from the menu on the right-hand side of the screen displaying the network. After selecting the ‘Apply’ command button, the revised network is displayed, with some nodes removed through the effect of the pesticide. The recalculated integrity measures are shown after the ‘Compute’ command is selected. In this example, the impact of applying Dimethoate 40 (dimethoate) and Hostathion (triazophos) is considered. The revised networks are shown in Fig. 9 (Dimethoate 40) and Fig. 10 (Hostathion). These results indicate that damage to...
the network is greater from the use of Hostathion than from the use of Dimethoate 40.

To reset the analysis and select the network for a different season, the ‘reset season analysis’ option is selected from the ‘File’ menu at the top of the screen.

Integrity measures have been calculated for a range of pesticide treatments and combinations of treatments. A summary of these results is shown in Table 1 (for spring applications) and Table 2 (for summer applications). In nearly every case, the effect of a pesticide on the clustering coefficient and path length is greater than the effect of knocking out a random node from the network. The choice of pesticide is important in determining the effect on the network. For example, the effect on the average clustering coefficient for summer applications of insecticides ranges from 100% (i.e. no change) to 106%. When combinations of insecticides are considered, the values range from 104 to 111%.

The calculated integrity measures are used to evaluate the structural damage caused to the network representing the ecological system by the application of pesticides represented in terms of deletion of network nodes. In accordance with the assumptions made, the structural damage measures indicate the measure of the functional damage caused by the application of pesticides to the real ecological system. These results show that the proposed methodology and analysis tool can be used to evaluate the effects of application of pesticides, and can indicate the difference between such effects of different pesticide treatments. This means that this kind of analysis can be used to prepare and support decisions about pesticide use scenarios and can help the selection of scenarios with minimal damaging impact on the ecological system. Note that

Table 1. Network integrity measures for the spring network before treatment and following the application of various combinations of pesticides. Significance levels are indicated by NS (u-value < 1.96), * (u-value 1.96–2.57) and ** (u-value > 2.57)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>C\text{ave}^a</th>
<th>Value (%)</th>
<th>Significance</th>
<th>l\text{avemin}^b</th>
<th>Value (%)</th>
<th>Significance</th>
<th>Network diameter</th>
<th>ISRF Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>0.128 (100)</td>
<td>–</td>
<td></td>
<td>2.190 (100)</td>
<td>–</td>
<td></td>
<td>4.0 (100)</td>
<td>–</td>
</tr>
<tr>
<td>Mean from single node</td>
<td>0.129 (100)</td>
<td>–</td>
<td></td>
<td>2.192 (100)</td>
<td>–</td>
<td></td>
<td>4.0 (100)</td>
<td>–</td>
</tr>
<tr>
<td>Pirimicarb</td>
<td>0.131 (102)</td>
<td>NS</td>
<td></td>
<td>2.186 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Dimethoate</td>
<td>0.133 (103)</td>
<td>**</td>
<td></td>
<td>2.178 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>0.132 (102)</td>
<td>**</td>
<td></td>
<td>2.187 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Fonofos</td>
<td>0.129 (100)</td>
<td>NS</td>
<td></td>
<td>2.190 (100)</td>
<td>NS</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Triazophos</td>
<td>0.136 (106)</td>
<td>**</td>
<td></td>
<td>2.191 (100)</td>
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<td>4.0 (100)</td>
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<td>NS</td>
</tr>
<tr>
<td>Pirimicarb + triazophos</td>
<td>0.139 (108)</td>
<td>**</td>
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<td>Triazophos + dimethoate</td>
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</tbody>
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^a C\text{ave} = average clustering coefficient.  
^b l\text{avemin} = average minimum path length.  
^c ISR = isolation node ratio.

Table 2. Network integrity measures for the summer network before treatment and following the application of various combinations of pesticides. Significance levels are indicated by NS (u-value < 1.96), * (u-value 1.96–2.57) and ** (u-value > 2.57)

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<td>Pirimicarb</td>
<td>0.133 (102)</td>
<td>**</td>
<td></td>
<td>2.180 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Dimethoate</td>
<td>0.125 (103)</td>
<td>**</td>
<td></td>
<td>2.173 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>0.125 (103)</td>
<td>**</td>
<td></td>
<td>2.183 (100)</td>
<td>NS</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Fonofos</td>
<td>0.131 (100)</td>
<td>NS</td>
<td></td>
<td>2.183 (100)</td>
<td>NS</td>
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<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Triazophos</td>
<td>0.139 (106)</td>
<td>**</td>
<td></td>
<td>2.191 (100)</td>
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<td>4.0 (100)</td>
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</tr>
<tr>
<td>Methiocarb</td>
<td>0.133 (102)</td>
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<td>2.173 (99)</td>
<td>**</td>
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<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Pirimicarb + triazophos</td>
<td>0.142 (109)</td>
<td>**</td>
<td></td>
<td>2.190 (100)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
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<tr>
<td>Chlorpyrifos + triazophos</td>
<td>0.142 (109)</td>
<td>**</td>
<td></td>
<td>2.190 (100)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Chlorpyrifos + dimethoate</td>
<td>0.137 (104)</td>
<td>**</td>
<td></td>
<td>2.176 (99)</td>
<td>**</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
<tr>
<td>Triazophos + dimethoate</td>
<td>0.145 (111)</td>
<td>**</td>
<td></td>
<td>2.182 (100)</td>
<td>NS</td>
<td></td>
<td>4.0 (100)</td>
<td>NS</td>
</tr>
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</table>

^a C\text{ave} = average clustering coefficient.  
^b l\text{avemin} = average minimum path length;  
^c ISR = isolation node ratio;
to evaluate the precise ecological meaning of these results would require field calibration of the proposed methodology and analysis tool. It may also be argued that the calculated percentage changes are small and may appear as natural quantitative fluctuations in the ecosystem. However, it is emphasised that the present modelling methodology is based on an abstraction at the level of species and environmental factors (e.g. species are considered as nodes of the network) and does not capture details of quantitative changes in the ecosystem (e.g. changes in the biomass of a species). In the context of the present analysis, the measured changes should be seen as structural changes in the ecosystem, which may imply very large quantitative changes in terms of detailed aspects of the ecosystem (e.g. in terms of changes in the biomass of a species).

5 DISCUSSION AND CONCLUSIONS
The available data regarding interaction between species are rather general. Knowledge of more specific interactions would allow more precise modelling of the ecological system and more exact evaluation of its integrity. Further literature-based studies and field studies are needed to establish the details of interactions between species. Data on the quantitative interactions between species and pesticides are scarce. The construction of a database of interactions, using literature surveys and field studies, would help to evaluate the ecological effects of pesticide application more precisely.

The importance of different combinations of species with regard to the integrity of the ecological network can be assessed using this tool. This approach could be used to assess the relevance of the indicator species selected by the Voluntary Initiative. The latter could be further evaluated by conducting surveys on the species identified by the model to be important to the integrity of the ecological system. In this way, the methodology and the tool could be calibrated using indicator species, and could also be used to identify new indicator species or combinations of species that can be used as equivalents of indicator species.

The network analysis tool can be used to determine the impact of different combinations of pesticides on the ecological system. This facility can be used to identify the least ecologically damaging pesticide strategies. With further development, the tool can be extended to consider fields with more refined structure (e.g. field headlands and field centres) or complex effects of pesticides (e.g. when the application of two pesticides together has non-additive joint effects, for example, by cancelling some of the negative side effects of one or both pesticides). The impact of pesticide use in these different areas could be assessed. This approach could be used to evaluate the impact on biodiversity of practices defined in Crop Protection Management Plan sections B4 (reduction in exposure to pesticides), B5 (encouraging field biodiversity) and B6 (conserving biodiversity in non-cropped areas).2,28

The key message from these results is that careful selection of pesticides can be beneficial to the overall ecological health of the area. From the point of view of the Voluntary Initiative, it endorse point B4 of the Crop Protection Management Plan,2 that farmers should choose their compounds with reference to their environmental impact. Some farmers will aim for control of the pest at minimal cost, whereas an environmentally better farmer will select compounds over the whole growing season that will achieve the required control with minimal environmental impact. It is crucial that any farmer only achieving level D on point B4 of the Crop Protection Management Plan should be encouraged to achieve at least the regulatory minimum level C.2

In order to help evaluate the Voluntary Initiative,2 various specific combinations of pesticides could be assessed using this tool. The choice of combinations of compounds should reflect the real issues deriving from relevant agronomic information. Depending on the data available, this tool can help to evaluate the effectiveness of the Voluntary Initiative on the farm scale or on the wider scale, depending on the information available.

Supplementary material
Supplementary electronic material for this paper is available in Wiley InterScience at: http://www.interscience.wiley.com/ipages/1526-498X/suppmat/.

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REFERENCES
Ecological network analysis of effects of pesticide use