The incidence function model as a tool for landscape-scale ecological impact assessments

Laura J. Graham, Roy H. Haines-Young, Richard Field

ABSTRACT

Landscape-scale approaches to assessing the impact of land-use change on species’ persistence are necessary because species depend on processes acting at varying scales, yet existing approaches to ecological impact assessment tend only to be site-based. A further major criticism of current ecological impact assessments is that they tend to be qualitative. Here we develop methods that apply the Incidence Function Model (IFM) in real urban planning contexts, by generating repeatable and comparable quantitative measures of ecological impacts. To demonstrate the methods for a case study (Nottingham, UK), we estimated landscape-scale measures of species’ persistence that indicate metapopulation viability. We based these on Nottingham’s landscape when urban developments were recently proposed, then adjust the land cover to include the proposed developments, and also for two projected landscapes where 10% and 20% of the original natural or semi-natural land cover is lost. We find that the IFM shows promise as a tool for quantitative landscape-scale ecological impact assessment, depending on the size of the impact. We detected minimal differences in the species’ viability measures between the original and post-development landscapes. This suggests that for small (around 2%) cumulative losses of natural/semi-natural space, current site-based approaches are sufficient. However, when the cumulative effect of continued development was modelled by increasing the losses of natural/semi-natural land cover to 10–20% of existing cover, the impact on many of the species studied was more substantial. This indicates that a landscape-scale approach is necessary for larger, prolonged and cumulative habitat losses.

1. Introduction

Increasing human population and industrialisation are leading to an increase in the numbers of people living in urban areas. In 2015, 54% of the global population lived in cities (The World Bank, 2017). The rising populations put increasing pressure on our cities, and the habitats and species contained within. However, urban green spaces provide a range of benefits to humans and biodiversity conservation (Aronson et al., 2017). Conservation of biodiversity is often in conflict with social and economic goals, such as city development (Ng Mei Sze and Sovacool, 2013). Nature conservation is frequently listed as a key issue in land-use conflicts (von der Dunk, Grêt-Regamey, Dalang, & Hersperger, 2011). It is increasingly recognised, however, that conservation needs to be integrated with social and economic issues (Brown, 2002). It is therefore necessary that urban planning be strategic at a landscape scale such that the increased need for development is met while having the least impact on the natural environment (Mörberg, Balans & Knol, 2007).

Protection for non-designated natural areas is available in the form of ecological impact assessments (EIAs). EIAs have been integrated into policy in many countries with varying levels of success (Wathern, 2013), and in some cases the information provision has been found to be insufficient (Drayson, Wood, & Thompson, 2015). An EcIA is a process which identifies, quantifies and evaluates the potential impacts of actions, such as developments, on ecosystems and their component species (Treweek, 1999). For example, EIAs are subject to the Environmental Impact Assessment Directive (Official Journal of the European Union, 2011) and also the Strategic Environmental Assessment (Official Journal of the European Union, 2001), though these are not compulsory for all developments. Additionally, EcIAs tend to only consider impacts on protected and priority species. Many non-protected species are nevertheless currently showing decline (Hayhow et al., 2016; Defra, 2013), and there are strong arguments for also investigating impacts on non-priority species and habitats.

A site-based approach to EcIA is argued to be insufficient (Mörberg et al., 2007). The spatial configuration of habitat is an important factor in species persistence (Opdam, Verboom, & Pouwels, 2003). Increasingly it is recognised that an understanding of landscape pattern and environmental impact assessments (EIAs). EIAs have been integrated into policy in many countries with varying levels of success (Wathern, 2013), and in some cases the information provision has been found to be insufficient (Drayson, Wood, & Thompson, 2015). An EcIA is a process which identifies, quantifies and evaluates the potential impacts of actions, such as developments, on ecosystems and their component species (Treweek, 1999). For example, EIAs are subject to the Environmental Impact Assessment Directive (Official Journal of the European Union, 2011) and also the Strategic Environmental Assessment (Official Journal of the European Union, 2001), though these are not compulsory for all developments. Additionally, EcIAs tend to only consider impacts on protected and priority species. Many non-protected species are nevertheless currently showing decline (Hayhow et al., 2016; Defra, 2013), and there are strong arguments for also investigating impacts on non-priority species and habitats.

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process is necessary to identify the impacts of land-use change on species, and that planning decisions need to be taken at a landscape scale (Hobbs, 1997; Mörterberg et al., 2007). As a result, it is crucial that a method for assessing landscape-scale impacts of urban development on species persistence be available. Landscape-scale approaches have been developed to identify habitat expansion areas (McHugh & Thompson, 2011), but it is also necessary to analyse the effects of habitat conversion at a landscape scale.

We propose that the incidence function model (IFM; Hanski, 1994) is an appropriate method to simulate the impacts of changes in the urban landscape on species persistence. The IFM is most applicable in highly fragmented landscapes (Hanski, 1999) where suitable habitat consists of small, discrete patches. Urban areas generally contain many small patches of remnant, managed and unmanaged habitat (McKinney, 2002). Unlike classical metapopulation models, the IFM is spatially realistic – it takes as an input the size and locations of the patches – which means it can be used to investigate the impact of the removal of patches within real landscapes (Hanski, 1994). The IFM also has the advantage of less-intensive data requirements than other such models: it can be parameterised using a snapshot of species occurrence (Etienne, ter Braak, & Vos, 2004; Hanski, 1999). Patch occupancy models, including the IFM, have previously been tested for the purpose of comparing the impact of different landscape configurations on the persistence of focal species (for example Heard, McCarthy, Scroggie, Baumgartner, & Parris, 2013; Wahlberg, Molainan, & Hanski, 1996).

In this paper, we aim to develop measures of landscape-scale species’ persistence which are comparable between landscapes, for the purpose of investigating the ecological impacts of proposed developments. We demonstrate that the IFM has potential as a tool for aiding EcIAs. We provide a proof of concept using the case study of Nottingham City with respect to urban development proposals put forward in 2005. We compare outputs of simulations for the original landscape (contemporary with the development plans), the landscape adjusted by removing habitat as specified by the proposed developments, and two projected future landscapes with further losses of 10% and 20% cover of natural and semi-natural broad habitat types.

2. Methods

2.1. Study site and data

We used the Nottingham City unitary authority as the case study area, and included a 2 km buffer to allow for dispersal from outside. Nottingham is a fairly typical medium-sized urban area (area 74.61 km², population c. 305,680) in the East Midlands of England. Nottingham is characterised by remnant woodland and grassland habitat within the city boundary, a greater proportion of freshwater than comparable urban areas, and surrounded by a higher proportion of arable land in the peri-urban areas.

We obtained maps of the proposed developments for the Nottingham City unitary authority from the Nottingham Local Plan (Nottingham City Council, 2005a). These proposed developments are those that have since been approved in the strategic plan and include residential, employment and mixed use. Maps were downloaded from the Nottingham City Council website for the North Side (Nottingham City Council, 2005b) and South Side (Nottingham City Council, 2005c). The study site and locations of proposed developments are shown in Fig. 1. We used Land Cover Map 2007 data (Morton, Rowland, Wood, Meek, Marston, Smith, & Simpson, 2011) for information about the spatial configuration and classification of habitat patches at the time when the developments were proposed.

We used a suite of indicator species to investigate the impacts of development on landscape-level species persistence. The species chosen had a range of habitat specialisms and dispersal abilities. Only species with dispersal distance < 10 km were included because longer-dispersing species have been shown not to be suitably dispersed limited to model metapopulation dynamics at the scale of this study (Graham, Haines-Young, & Field, 2015). We recommend that only species with a dispersal distance approximately ≤ \( \sqrt{\text{studyarea}(\text{km})^2} \) be included. Therefore, species with a longer dispersal distance are more appropriate for analysis of larger study areas (e.g. regional, rather than city scale). The species, their specialisms, habitat associations and dispersal abilities are given in Table 1.

For each of the landscapes under comparison, we created modified maps which reflect the species’ habitat requirements shown in Table 1. So that patches were portrayed in the way species use them, rather than how they are viewed by humans, we dissolved all artificial boundaries in the LCM 2007 data. The artificial boundaries were those which would be considered boundaries by humans, but not by the species using the habitats, that are caused by differing land ownership, separation of similar habitat types, and paths and roads ≤ 3 m wide.

Species occurrence data for bird species were provided by Nottinghamshire Birdwatchers and the amphibian data were downloaded from the National Biodiversity Network Gateway using the R package ‘rmbn’ (Ball & August, 2013). The resolution of the species’ data (2 km x 2 km) is coarser than that required as input to the model (patch-level occupancy), so we employed a downscaling technique. For each grid cell reported as occupied, we assigned species’ occupancy to patches by area-weighted sampling, a method which was found to produce the most realistic species occupancies after simulation with the IFM (Graham et al., 2015). Within each occupied 2 km x 2 km cell, patches are randomly allocated occupancy with a higher probability the larger the patch. The proportion of patches occupied within a cell is equal to the proportion of 2 km x 2 km cells occupied in the landscape. To account for the uncertainty in the downscaling method, a set of 200 starting conditions of species’ occurrences was created using this method. These species’ occupancy patterns are the input data to the IFM.

2.2. Developments and projected loss landscapes

To create a ‘developments’ layer, we georeferenced the Local Plan maps to match the LCM 2007 data using ArcMap 10.0, then digitised the proposed developments. The developments layer was overlaid on the LCM 2007 data and any corresponding non-urban or suburban polygons were updated to urban to simulate the effect of development.

For further comparison, and to investigate the effects of cumulative developments over time, we created two additional landscape maps: projected maps of 10% and 20% habitat loss. These maps were created based on the idea that development acts as a contagion on the landscape, and that natural spaces closest to development are more vulnerable (Laurance, 2008). We methodically removed patches defined as terrestrial habitat (i.e. any patch falling in the classes listed in Table 1 except freshwater) in order of distance to the nearest development (closest first) until 10% and 20% of original habitat cover had been removed (see Fig. 2 for maps of these projected future landscapes).

2.3. Model simulation

The incidence function model (IFM, Eq. (1)), a stochastic patch occupancy model developed by (Hanski, 1994), allows long-term predictions of metapopulation persistence in a network of habitat patches to be made through estimation of colonisation and extinction rates. The occupancy of a patch \( i \) is given by \( J_i \), where \( J_i \) is a balance of colonisations (\( C_i \)) and extinctions (\( E_i \)).

\[
J_i = \frac{C_i}{C_i + E_i - C_i E_i}
\]

(1)

The extinction probability is calculated following the assumption that the number of individuals is directly proportional to the area of the patch they occupy. Extinction is affected by population size, so \( E_i \) can therefore be expressed as a function of \( A_i \):
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