Red Squirrels United - Evolving IAS grey squirrel management techniques in the UK and Ireland

D3 – Ecosystem function restoration assessment:

Outcomes of monitoring evaluations on all year 1 conservation actions

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Summary

The purpose of this action (D3) is to evaluate and inform the implementation of grey squirrel management and to provide an ecosystem restoration assessment for project areas. This report summarises the year 1 (August 2016- August 2017) progress of Action D6 to assess the impact of the conservation actions C1-C4 undertaken during the Red Squirrel United (Sciuriosity) project.

A delay in progress has arisen as there is no specific provision for standardised and integrated data collection and collation in the project (*e.g.* project app or Access database). Specific requirements for the quality and frequency of data submission were determined by NU in Preparatory Action A3; these were actively communicated to all partners early in the project. In order to ensure high data quality, NU developed data recording templates which aim to be standardised and specific to the RSU project, but also specific to the partners' existing projects and current routines, so they remain familiar to operators. However, finalising recording sheets has been slow due to the time taken for communication and testing of spreadsheets with all RSU partners. Some initial data has been provided but requires significant checking – especially of the documentation of effort.

NU has started developing the models required to evaluate the conservation actions but this has been limited by data provision. NU have been progressing these models by retrieving associated metadata (e.g. habitat, weather and environment information appropriate to the correct timeframe and spatial areas), and developing the code required for the model structures. The small sections of the data from year 1 conservations actions with suitable effort variables have been used to build model structures. All models will require further development as more data becomes available to determine the correct temporal period over which to construct the models. The model frameworks are being coded using the R software package and associated code packages which are all freely available and enhance the suitability of the model framework for post project use.

As the models are developed and tested NU will consult with the project partners to determine the most suitable methods of feedback of the model outputs to inform ongoing control.

There is an urgent need to finalise all recording templates as they are essential to produce the data required to assess the success of the RSU conservation actions and to allow the project to develop.

Summary of actions included in deliverable D3

The two main areas of work being coordinated and assessed by NU within Action D3 involve data analysis and modelling to quantify ecosystem restoration assessment and evaluate and inform the implementation of grey squirrel management across actions C1-C4. Both areas of work are dependent on the provision of data from project partners, and use data on sightings of red and grey squirrels, monitoring data from regular camera trapping and records of grey squirrel control, including live capture and shooting effort data.

Evaluate and inform the implementation of grey squirrel management

The aim is use data collated on grey squirrel control, including live capture and shooting, to assess current control practises with the aim of optimising control in time and space. Specifically we will assess:

(1) rates of grey squirrel removal per unit control effort through time
(2) effect of management interventions on grey squirrel abundance/range

The aim is to use the findings from each of the conservation actions to inform the next phase of management in each area within the timeframe of the project.

Provide an ecosystem restoration assessment for project areas

To assess the impact of the control of greys squirrels on the conservation of the red squirrels we will combine monitoring, sightings and control effort data in an assessment of:

(3) change in abundance and range size of native red squirrels in response to grey culling
(4) impact of management on the proportion of grey squirrels carrying infections

To do this NU have developed a modelling framework and determined the associated data requirements. The models will be used to inform real time management actions and costed future management scenarios.

Progress in Year 1

This report covers the Year 1 period Sep 2016 to Sep 2017 and reports on action D3 in this time. The prep action A6 report covered the period from Nov 2015 to Aug 2016. Action A6 highlighted that the analysis of field data to evaluate Sciuriosity actions in real time is dependent on the provision of sufficient, good quality data.

The report reported differences in pre-existing protocols for data collection, parameters recorded and data quality. The majority of year 1 has been spent developing robust data recording mechanisms with all partners and working towards getting these implemented correctly.

Year 1 progress has with modelling has been delayed by data provision issues. We provide an update on the four analytical objectives that contribute to the assessment of grey squirrel management. For each aspect of the analysis, we include a presentation of the model structures as well as the progress, limitations and challenges associated with each type of model.

Summary of preparatory actions (A6)

Agreement on data reporting protocols

Meetings and site visits to share progress and disseminate advice on data recording protocols have taken place with all partners. An essential part of efficient and high quality data gathering is the preparation of a data recording template that suits the requirements of the project as well as each partner's needs, can handle a large volume of data, and allows assembling the datasets.

There is no specific provision for standardised or integrated data collection and collation in the project (*e.g.* project app or Access database) and the project partners all have different ways of working and recording data. To overcome this with minimum cost and disruption data recording spreadsheet templates were designed by NU that match those objectives and incorporate required changes to existing data recording sheets (Table 1) and include:

- incorporate solutions to limit recurrent issues identified by NU in previous records (*e.g.* drop-down menus to eliminate typing errors), additional variables
- accommodate additional data entry necessary for the analysis (*e.g.* effort, number of traps, area)
- include partner-specific requests (*e.g.* camera logs in UWT)

Partners undertaking conservation actions C1-4 are responsible for collecting, recording and sharing data with NU. NU is responsible for the processing, analysis and interpretation of data and sharing/ dissemination of the findings.

Table 1: Examples of previous issues and subsequent changes agreed with partners for RSU data collection.

Variable	Previous issues	Changes
Daily count within session	Data were recorded for individual captures and per session; daily count of captures was not recorded.	Both time scales (session and day within session) can now be recorded, as required by robust models
Control session	The definition of a trapping session differed between sites. Ideally, a session is a series of consecutive control days.	Control effort is misrepresented if the reported duration includes non-control days, leading to a bias in the model outputs A session is now defined as a series of consecutive control days for all partners.
Blank traps and bycatches records	By summarizing catch data over a trapping session, blank traps and bycatches cannot be accounted for on a daily basis.	Traps found blank or with bycatch must be accounted for as they lead to a reduced effort. Partners have expressed difficulties in obtaining this level of summary data. Discussions on ways to record this information efficiently are welcomed for all RSU partners.
Effort in space: trapping area	Trap locations were recorded only when successful, so that the trapping area could not be determined.	An estimation of the area controlled during each trapping session is essential to express capture rate in a consistent and standardised unit. The location of every trap is now recorded, allowing effective trapping area to be estimated as the convex hull created by the most outer points of the surface covered during a given trapping session.
Effort in space: shooting area	Shooting locations were only recorded as location of greys shot, not allowing the calculation of the shooting area.	Discussion with all partners suggested that shooting area can be provided as an estimation of shooting area by the rangers (also walking distance at NWT) for each shooting session.

Solutions and recording requirements were discussed with all partners and integrated within the data recording templates. Existing records were used in order to retain a familiar format for the operators. As a consequence, all partners were required to test template versions of the new electronic recording form produced and emailed by NU, and to communicate potential issues or required amendments or preferences before amendments were made, and an updated version was sent again. Changes were discussed and demonstrated, via email, in person and on-site.

Major challenges in Data provision

The speed of development of the recording templates has been dictated by the input from the conservation action partners to test and implement the new designs that have been created by NU. NU have been unable to finalise the templates and commence with database collation as issues (*e.g.* errors in the sheets) have not been highlighted or communicated immediately.

Overall this process of developing and testing the templates has been much slower than agreed and has been hard to implement as each project partner has been keen to preserve or integrate their existing methods of work with the RSU data needs. Ideally a project database would have been used but data sharing in this way was impossible to implement in a short time to a project with multiple existing working practices.

Recording operational effort has been a major change for most partners and has been difficult to obtain consistently in time and space. Records of effort in time (*i.e.* duration) improved as a result of precisely redefining a session as a series of consecutive days on the recording templates. Records of effort in space (*i.e.* control area) is a new parameter to record for some partners; it has been a difficult variable to obtain consistently (especially for shooting) (Table 1, page 5).

Data recording quality remains a problem and needs to be addressed by partners, including preventable errors such as:

- Typos or misnaming woodlands
  - *e.g.* Watersmeet /Watersheet
- Woodlands classified incorrectly and/or inconsistently into bigger zones
  - *e.g.* some woodlands classified in all four zones
- Dates that are obviously wrong make other dates questionable
  - *e.g.* surveys dated 2018; is it 2017 or is the whole date wrong?

Data checking and cleaning is the responsibility of the partners collecting the data and must be done before sharing datasets with NU. Unchecked errors can have large consequences for analysis as they lead to:

- data to be omitted from the analysis
  - *e.g.* mis-spelt location names hinder matching sessions to woodland characteristics, landscape, individual data
- resource to localise those errors (detracting from data analyses)
  - At the current testing stage, data errors delay model assessment as it is tedious process to determine whether outcomes are due to data errors or issues with the model structure in development.

Current status within global modelling framework

The global modelling framework was set out in the report on A6 and is summarised in Box 1. Step 1 was completed in the Prep Action A6. Steps 2 and 3 are in progress and subsequent steps are contingent on Step 2 being completed. The supply of high quality data (Step 2) is a prerequisite for further development of the modelling structures (Step 3), and the frequent data reporting (Step 2) is required to assess the ongoing control (Step 4).

NU have been progressing the development of processes for data processing, including cleaning, standardising and assembling datasets and have started developing the model structures. However, the RSU database must increase in the number of high quality datasets (by monthly input from all partners) so that the analytical approach can be finely tuned to the RSU data. RSU partners are presented with various challenges associated with data requirements (new parameters to record, increased frequency of data digitisation), however delays in finalising recording templates and compromises in data quality will reduce the volume of conservation action data that can be used in Action D3. In turn this will lower the level of precision and accuracy that the models can achieve, hence their usefulness in future control planning. The completion of the recording templates was raised at the Project Management Board in September and the provision of data has been added to the RSU Project Management Board Risk Register.

In order to complete Step 2, data recording templates must be finalized. The first recording templates were suggested to all partners early in the project: February 2016 (RSTW), May 2016 (NWT), December 2016 (UWT), and October 2016 (LWT). However, by September 2017, templates have only been finalised by NU for NWT partners and are ongoing with LWT and UWT partners. RSTW partners did not adopt the suggested format for their data collection.

Box 1: Global modelling framework

1. Assemble data
Review data, identify strengths and weaknesses, and develop methods to address objectives for each site.

2. Standardize datasets
Determine specific requirements for data collection with regards to environmental factors and control effort, produce data accordingly.

3. Develop the model structure
Occupancy models, removal data models, cost-benefit models.

4. Assess impact of control
Models progressively improved by adjusting for natural and site-specific variations with increasing amount of high quality data.

5. Rerun and update
Update models using high quality data, produce more precise inferences.

6. Transfer and replicate
High quality data representative of natural variations and control effort allow transferring inferences from conservation actions to other areas.

As a consequence a large proportion of year 1 has been spent preparing template recording sheets and the model development has been delayed.

Progress towards evaluating the implementation of grey squirrel management

Role of ecological models, assumptions and requirements

Ecological modelling will be used to evaluate several aspects of the conservation actions. Ecological models allow the integration of multiple types and scales of data to investigate and understand the dynamics of complex ecological systems. In the case of this project, to understand the changes in grey squirrels populations brought about by culling and the consequent impact on red squirrels. The structure of each model is developed based on assumptions that describe underlying ecological processes that are uncertain and often unobserved. High quality data allow robust models that can provide a reliable basis for the development of management support and policies.

Squirrel count data (*e.g.* numbers observed or captured) can be used to gather information about their overall abundance. However in order to consider count data as an index of abundance and potentially investigate changes through time, it is necessary that:

(1) Count data are standardised across datasets

A standardised methodology would record all animals observed during a fixed duration at diverse locations, however it is not practical or feasible to standardise methodologies across all RSU partners as practices, protocols and priorities vary.

Instead, count data obtained by all partners must be standardised according to the methodology used to obtain the data. The effort involved in data collection must be described precisely in time and space by each partner and for each session, so that count data can be adjusted accordingly.

(2) We have a good estimate of the probability of detection

Comparing count data as raw numbers assumes that the probability of detection is the same across all datasets compared. For instance when comparing captures or sighting numbers in different habitats, the ratio of the counts only reflects the ratio of the abundance if the chance of seeing or catching an animal is similar in all habitats. Similarly by sampling a given location through time, a change in count data only implies a change in abundance if the detection probability remains identical through time. It is unlikely that the detection probability is comparable through time and space. It is therefore essential to determine the major factors influencing detection probability. This relationship is likely complex and varies with habitats and through time with potential interactions, it may also depend on the squirrel demographics throughout the year, and likely vary between the conservation actions due to differences in landscape and climate. Partners must accurately record all the parameters of their methodology that potentially influence detection probability (*e.g.* sampling or control effort as a duration of time and area surveyed and number of devices or observers, time of year, presence of bait). Alongside this data relevant environmental metadata must be identified and retrieved by NU for all observations. Detection probability will be a component at the basis of the structure of all the models included in this analysis.

The systematic and accurate recording of effort in space and time is essential for the following analyses.

Materials

All ecological models are being developed using the R environment and specific details are given below. To create these model structures several specialised packages have been used:

- to read shapefiles and process spatial data: geosphere, spdep, raster, rgdal, rgeos, maptools, sp, tmap, dismo
- to read and compile RSU partners' records: readxl, reshape, tidyr, rnrfa, plyr, dplyr
- for data illustration: ggplot2, ggmap, lattice
- for modelling: unmarked, pscl, lme4
- for data editing: stringr, zoo, lubridate

Data Provision: From Year 1 Conservation Actions

Data recorded using the project protocols are reported in Table 2. The majority of the conservation action has been through control sessions (shooting and trapping). NWT have also been using cameras for regular monitoring. All conservation actions have recorded more data but this is not yet in a format compatible with modelling. The largest issue with the recorded data is the lack of consistency in reporting of effort data.

Table 2: Summary of data sent in the agreed format to NU by partners, by mid-September 2017

Partners:		NWT	LWT	UWT
Data collection start		01/12/2016	03/01/2017	26/06/2017
Data collection end		19/06/2017	31/03/2017	25/08/2017
Total duration		~6months	~3months	~2months
N grey killed		170	71	50
N grey seen		75	94	0
N red recorded		67	4	0
N sessions total		248	48	41
N control sessions		125	48	41
N monitoring sessions		123	0	0
N sessions per method	Camera	107	0	0
	Feeder	14	0	0
	Shoot	89	22	7
	Sighting	2	0	0
	Trap	36	26	34
Effort data summary		45 control sessions without effort data	Effort data lacking	Effort data mostly lacking

Evaluate and inform the implementation of grey squirrel management

Rates of grey squirrel removal per unit control effort through time

The rates of grey squirrel removal, and numbers of control and monitoring sessions are expected to vary between partners, due to the different management approaches being undertaken (*e.g.* early warning versus eradication). However there are also differences in the volume of data due to project starting points, staff structures and also due to the frequency of data sharing and data quality (Table 2, page 9).

The lack of effort data recorded is currently a major constraint to the analysis. Missing records by NWT partners mostly occurred during the initial part of the data collection (43/45 sessions Dec 2016-March 2017) and have improved notably in recent months.

LWT and UWT partners have not provided the required information. LWT partners faced delays and difficulties retrieving data related to turn-over of staff. UWT partners provided inaccurate records (missing trap location information) that do not allow calculating control areas. Data sent by both partners are not suited for analysis. RSTW partner did not use the suggested template for their data collection and did not send records in a format that allows efficient processing and analysis of data.

Discussion is on-going with LWT and UWT partners to attempt matching effort data with previous records from within the project. Most data recording issues have been resolved so using the agreed recording format will generate records that meet the standard required for analysis.

Effect of management interventions on grey squirrel abundance/range

Structure and requirements of removal models

Removal models can be used to estimate population abundance while removing individuals from a population. The count of grey squirrels captured and culled constitute removal data, and will be used in removal models to investigate the population dynamics of populations under control. Removal models are hierarchical in that they contain several stages which each correspond to a precise assumption that is estimated using the removal data (Figure 1).

An overview of the complex structure of the removal model designed for the RSU project is illustrated in Figure 1. The structure contains several assumptions. Through each of them, and by incorporating relevant environmental variables at each stage, the model aims to estimate the abundance of grey squirrel that is represented by the daily captures (y1 to y5) and the sum of daily captures (Y).

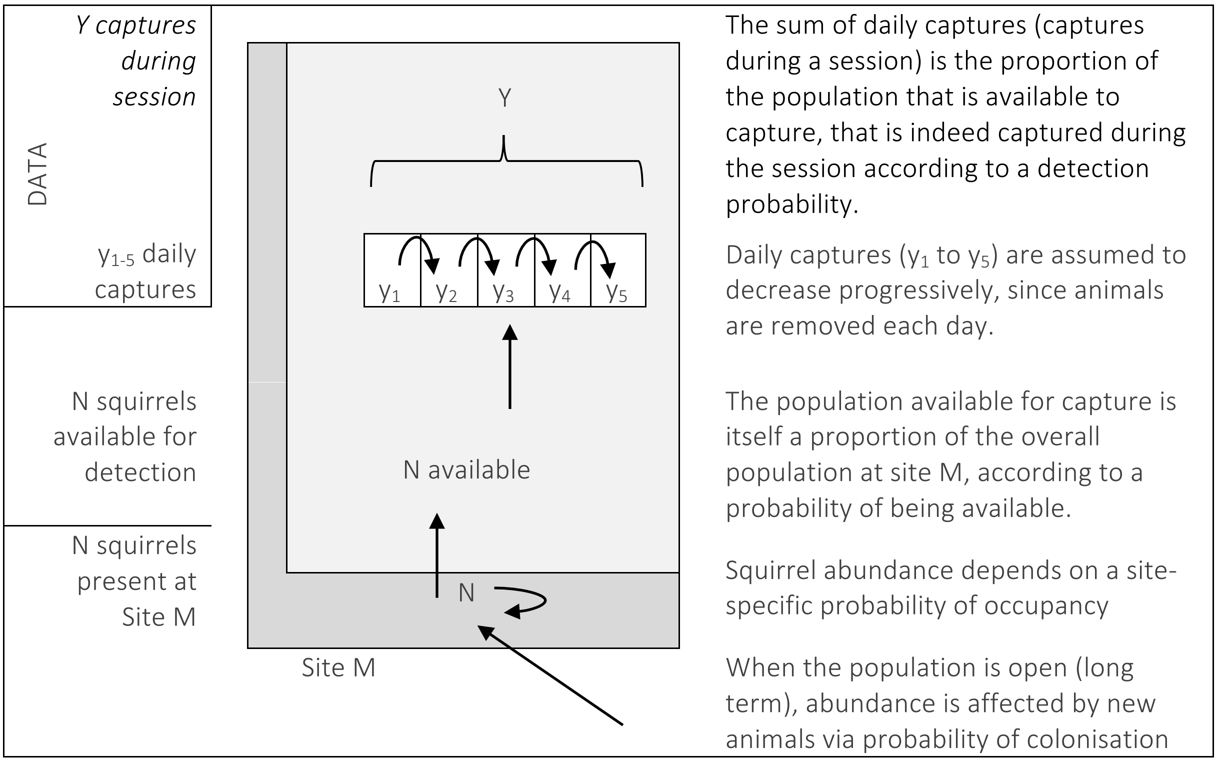

Figure 1: Overview of a grey squirrel removal model structure.

Removal data (number of squirrel captures) need to be standardised by characteristics of the control effort such as: duration of control session, trapping density, frequency of trap-setting, number of shooters, control area.

Models will investigate the relationship between captures and environmental factors, in order to quantify the effectiveness of the control operations. In order to assess changes in the populations through time, the factors driving and describing abundance will first have to be estimated with high precision. It is essential for these models to be robust and finely tuned before the effectiveness of different control regimes can be reliably assessed. It has not been possible to further develop these models until a large quantity of data covering a larger time period are available.

Challenges and limitations

The assumptions made at each stage of the removal model must be tested at relevant ecological scales so that the overall structure reflects the ecological and methodological processes that lead to number of grey squirrels caught each day during a session.

Determining the temporal and spatial scales at which those assumptions apply is a part of the analysis. For instance, one assumption is that the probability of capture decreases each day of a control session (*i.e.* from y1 to y5 on Figure 1). This is because the individuals captured are removed each day, therefore they cannot be captured again, nor are they replaced (assumption of closed population). As a result, the probability of capturing a grey squirrel under a reasonable probability of detection, must decrease each day within a session.

The probability of detection during the whole session is a function of the assumption of declining captures; the daily probabilities are linked to the overall detection probability. Therefore if a decrease in daily captures is not observed throughout sessions, the probability of detection during a control session is assumed by the model to be very low. This in turn leads to an overestimation of the squirrel abundance; implying that a squirrel captured within very low detection probabilities must reflect a very high abundance.

This difficulty in estimation implies that the data collected are not representative of the processes we are attempting to quantify. We can improve our estimation with more data collected using a similar methodology. This allows us to determine what other variables may influence the trend observed, and incorporate them into the general model.

The time scales used within the model must be ecologically meaningful to generate reliable estimations of the processes involved however these can also be very different and are often dictated by partners' practices. As partners apply multiple methods (shooting and live capture with or without bait) in varying landscapes, comparing and contrasting the effect of external parameters is challenging. When many parameters vary between observations, the number of observations that can be considered repeated and used for contrasting is reduced. For instance, a potential factor can be the index of the primary period when a given session took place (Figure 2). Each primary period is attributed an index number reflecting its ranking along a chronological order within each site. This index will have different meaning for NWT partners than for others while it reflects other criteria defining it (*e.g.* duration, time of year). With more primary periods being recorded, the index as a factor can be contrasted and models can be used to investigate a related trend. This issue makes modelling a small, temporally constrained dataset difficult but will improve with a growing dataset.

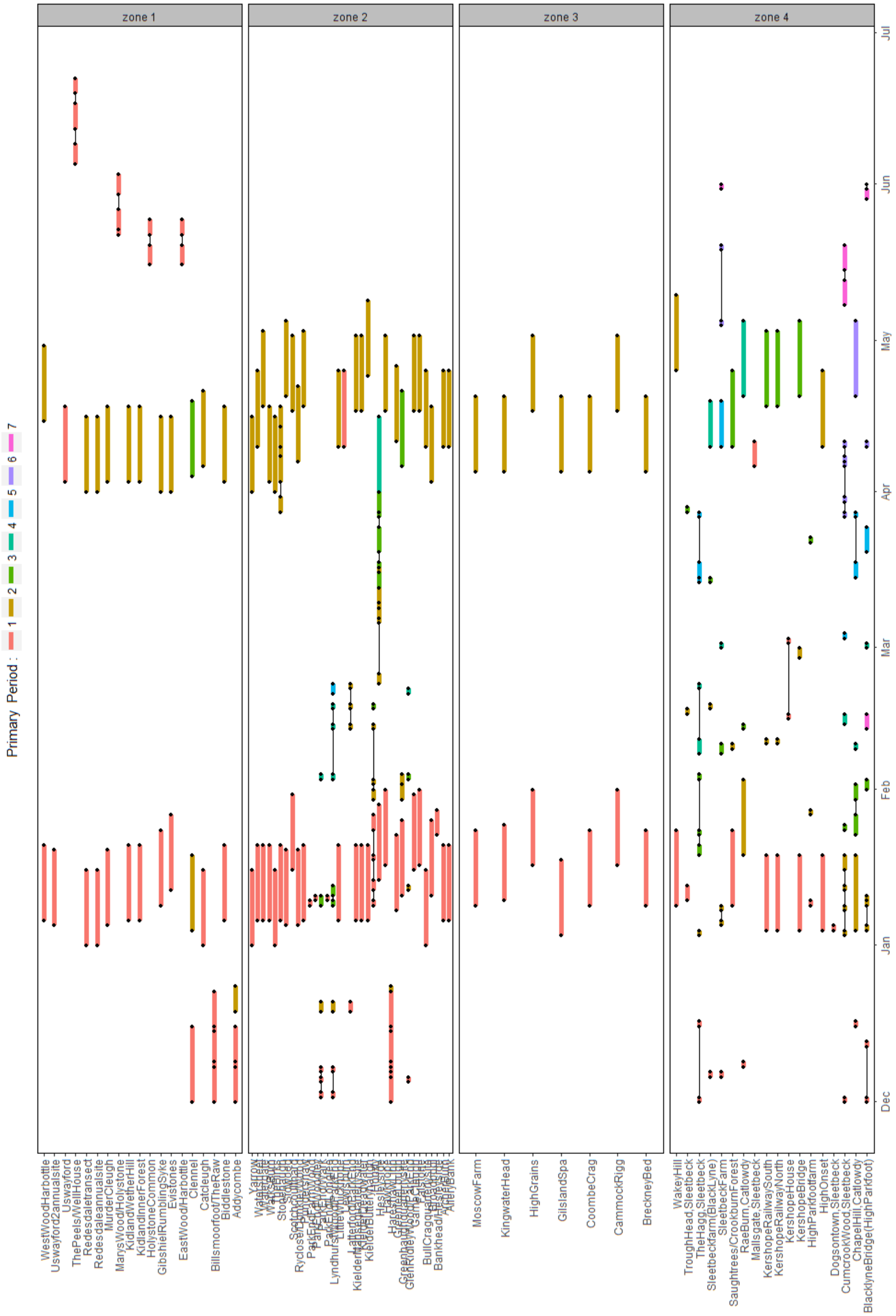

Figure 2: Example of partitioning of primary periods for NWT partners red and grey squirrel count data.

Provide an ecosystem restoration assessment for project areas

Change in abundance and range of native red squirrels in response to grey culling

Occupancy modelling

The effect of control operations on red and grey squirrel populations will be investigated using occupancy modelling. A particular focus will be on areas around stronghold boundaries with the aim to assess how these boundaries shift through time in relation to control operations.

Occupancy models will estimate the probability of red squirrel being present given particular environmental conditions. Presence/absence data are collected by the partners, usually through regular monitoring with camera traps; some environmental variables associated with each observation are retrieved by partners (*e.g.* date) and mostly by NU using the location and date of the observation (*e.g.* daily rainfall, percentage of broadleaved forest within 1km).

Detection is imperfect (*i.e.* individuals may be present yet unseen), to get a better estimate of detection the models require data from multiple visits to sample sites to adjust for the detection process. A few environmental variables potentially influencing the detection process are collected by partners (*e.g.* observer, method) and mostly computed by NU (see metadata).

Occupancy cannot be assessed before the probability of detection is reliably estimated. There is currently an insufficient volume of data to proceed with this analysis.

Progress: metadata and scales

Robust models using high quality fine scale data are necessary to investigate the relationship between culling practices at these locations and grey squirrel abundance. Those models may then inform the required control practices associated with low levels of grey squirrels, and potentially allow red squirrels to expand instead.

Partners have been relying on annual monitoring to assess the response of red squirrel occupancy in relation to the control operations. The data used in this new model will use finer scale data, which will allow us to investigate the processes driving red squirrel abundance more accurately.

Metadata were retrieved for the data provided by partners in the agreed format. Scripts were written in preparation of future data being received. Metadata include (Table 3) site-dependent variables (such as habitats and other landscape descriptors) and time-dependent variables (such as weather at fine and medium scales, life history events at time of year).

The effect of these variables, and potential interactions, will be investigated at several temporal and spatial scales on the several ecological processes incorporated into the models.

Table 3: Metadata retrieved/prepared for retrieving by NU for the data provided/to be provided by partners.

Type of variables	Example of variables	How datasets were obtained	Scales computed for analysis
Habitat according to National Forest Inventory and EDINA	Conifer Broad leaf Fell trees Young trees Bare land Shrubs Agriculture Grass ..	Hard copy of the NFI dataset for UWT was obtained on CD after direct request. Datasets available as shapefiles online: https://www.forestry.gov.uk/fr/beeh-a2uegs http://digimap.edina.ac.uk/environment	Data are computed spatially, aggregated at the woodland area, control area, and at several values of radius (***e.g.*** 1km, 2km) around relevant locations (***e.g.*** central control area location). At each scale, each habitat category is expressed as a percentage cover of the whole area.
Landscape data	Distance to urban areas River cover Road type and cover Urban categories	Specific to each area	Averaged at each spatial scale (woodland, control area, point location).
Small scale weather	Cloud cover Percentage moon illumination Temperature Wind speed Humidity Barometry	Available online, for example: www.timeanddate.com/weather/@7297704/historic?month=6&year=2016	Provided as a daily values. Also computed - Over the session - During time since last session
Larger scale weather	Minimum, mean, and maximum temperature Hours of sun Rain (mm) Number of air frost days Number of rain days (>1mm)	Available online: http://www.metoffice.gov.uk/pub/data/weather/uk/climate/datasets/Tmax/date/England_E_and_NE.txt	Provided as monthly and seasonal values. Also computed as - Difference with previous month - Value during previous month/season
Life history events	Breeding, litter, gestation	Literature	The month of year for each session is associated with each stage of life history

Impact of management on the proportion of grey squirrels carrying infections

Model aims

The occurrence of disease will be monitored over time, in order to assess its relationship with various factors such as the presence of red squirrels, culling of grey squirrels, control practices, effort, spatial distribution, and determine whether any impact of the incidence is affected by habitat and landscape variables.

The tissue samples required for this analysis are not yet collected and/or recorded. The metadata involved in this analysis will require being computed at several scales and matched to tissue sample data as well as the general population at the time of sampling.

Progress: recording templates and tissue analysis

Data recording templates were updated in order to accommodate and automate tissue sample data to other information previously collected on individual squirrels; discussion with partners in order to finalize this adaptation is ongoing.

Next Steps

The plan of work for the next year includes:

1. Finalising the data recording templates.

With all project partners, as quickly as possible to enable to regular flow of data for the modelling. To do this NU need to:

- Plan meetings and site visits to discuss data recording with RSU partners (including new recruits)
- Incorporate tissue sampling information to templates

This will also require partners with responsibility for conservation actions C1-4 to:

- Improve communication, designate a contact person to communicate with NU
- Prioritise finalising data collection templates
- Provide all RSU data in the agreed format
- Partners to provide past RSU data in agreed format

2. Model development.

With more data available NU will work on the model structures and investigate the appropriate scales for the models. We will also communicate with project partners to identify:

- Best methods for communicating findings with partners (what is useful)
- How to inform management planning, to do this we need an understanding of the current way control is planned, *e.g.* which woodlands are targeting (and where is effort lacking)

3. NU will host a funded Italian intern who will carry out least cost pathways modelling in GIS to link habitat suitability mapping to the early warning system development.

R packages references

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Reading shapefiles and processing spatial data

Robert J. Hijmans (2015). geosphere: Spherical Trigonometry. R package version 1.5-1. http://CRAN.R-project.org/package=geosphere

Roger Bivand, Gianfranco Piras (2015). (spdep) Comparing Implementations of Estimation Methods for Spatial Econometrics. Journal of Statistical Software, 63(18), 1-36. URL http://www.jstatsoft.org/v63/i18/

Bivand, R. S., Hauke, J., and Kossowski, T. (2013). (spdep) Computing the Jacobian in Gaussian spatial autoregressive models: An illustrated comparison of available methods. Geographical Analysis, 45(2), 150-179.

Robert J. Hijmans (2015). raster: Geographic Data Analysis and Modeling. R package version 2.5-2. http://CRAN.R-project.org/package=raster

Roger Bivand, Tim Keitt and Barry Rowlingson (2016). rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 1.1-8. http://CRAN.R-project.org/package=rgdal

Roger Bivand and Colin Rundel (2016). rgeos: Interface to Geometry Engine - Open Source (GEOS). R package version 0.3-19. http://CRAN.R-project.org/package=rgeos

Roger Bivand and Nicholas Lewin-Koh (2016). maptools: Tools for Reading and Handling Spatial Objects. R package version 0.8-39. http://CRAN.R-project.org/package=maptools

Original S code by Richard A. Becker, Allan R. Wilks. R version by Ray Brownrigg. Enhancements by Thomas P Minka and Alex Deckmyn. (2016). maps: Draw Geographical Maps. R package version 3.1.0. http://CRAN.R-project.org/package=maps

Pebesma, E.J., R.S. Bivand, 2005. Classes and methods for spatial data in R. R News 5 (2), http://cran.r-project.org/doc/Rnews/

Martijn Tennekes (2016). tmap: Thematic Maps. R package version 1.4. http://CRAN.R-project.org/package=tmap

Robert J. Hijmans, Steven Phillips, John Leathwick and Jane Elith (2016). dismo: Species Distribution Modeling. R package version1.0-15. http://CRAN.R-project.org/package=dismo

Reading and compiling records

Hadley Wickham (2016). readxl: Read Excel Files. R package version 0.1.1. http://CRAN.R-project.org/package=readxl

Hadley Wickham (2016). tidyr: Easily Tidy Data with `spread()` and `gather()` Functions. R package version 0.4.1. http://CRAN.R-project.org/package=tidyr

H. Wickham. Reshaping data with the reshape package. Journal of Statistical Software, 21(12), 2007.

Claudia Vitolo (). rnrfa: UK National River Flow Archive Data from R. R package version 1.3.0. http://CRAN.R-project.org/package=rnrfa

Hadley Wickham (2011). The Split-Apply-Combine Strategy for Data Analysis. Journal of Statistical Software, 40(1), 1-29. URL http://www.jstatsoft.org/v40/i01/

Hadley Wickham and Romain Francois (2015). dplyr: A Grammar of Data Manipulation. R package version 0.4.3. http://CRAN.R-project.org/package=dplyr

Illustration

H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2009.
D. Kahle and H. Wickham. ggmap: Spatial Visualization with ggplot2. The R Journal, 5(1), 144-161. URL http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf
Sarkar, Deepayan (2008) Lattice: Multivariate Data Visualization with R. Springer, New York. ISBN 978-0-387-75968-5
Erich Neuwirth (2014). RColorBrewer: ColorBrewer Palettes. R package version 1.1-2. http://CRAN.R-project.org/package=RColorBrewer

Statistical modelling

Ian Fiske, Richard Chandler (2011). unmarked: An R Package for Fitting Hierarchical Models of Wildlife Occurrence and Abundance. Journal of Statistical Software, 43(10), 1-23. URL http://www.jstatsoft.org/v43/i10/
Achim Zeileis, Christian Kleiber, Simon Jackman (2008). Regression Models for Count Data in R. Journal of Statistical Software 27(8). URL http://www.jstatsoft.org/v27/i08/
Douglas Bates, Martin Maechler, Ben Bolker, Steve Walker (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Data formatting and editing

Hadley Wickham (2015). stringr: Simple, Consistent Wrappers for Common String Operations. R package version 1.0.0. http://CRAN.R-project.org/package=stringr
Achim Zeileis and Gabor Grothendieck (2005). zoo: S3 Infrastructure for Regular and Irregular Time Series. Journal of Statistical Software, 14(6), 1-27. doi:10.18637/jss.v014.i06
Garrett Grolemund, Hadley Wickham (2011). Dates and Times Made Easy with lubridate. Journal of Statistical Software, 40(3), 1-25. URL http://www.jstatsoft.org/v40/i03/