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

D3 – Ecosystem function restoration assessment:

Outcomes of monitoring evaluations on conservation actions, Year 2 review.

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Summary

The purpose of Action D3 is to evaluate and inform the implementation of grey squirrel management and to provide an ecosystem restoration assessment of the project areas where conservation action is undertaken. This review reports on the outcomes of monitoring evaluations on conservation actions undertaken in year 1 and year 2 (August 2016- August 2018) within the Red Squirrel United (Sciuriosity) project.

The modelling element of action D3 has not been able to progress as anticipated, as data from the conservation actions has been limited. The occupancy and removal models that we have developed will be used at the end of year 3 to evaluate the overall impact of conservation actions. We have analysed the data provided to explore trends in management activities through time. We have highlighted the difference in management strategies across the conservation actions ranging from intensive trapping, covering large areas where squirrels are abundant to much more targeted approaches with more monitoring and surveillance where eradication has reduced the population densities.

In order to explore the management strategies in more detail we developed a simulation model to generate outputs for a range of management scenarios. The simulation model uses available data on squirrel population dynamics and their known interactions with the environment such as season and habitat. We can then apply management scenarios to generate data outputs that can be modelled with the occupancy and removal models that we will also use to assess the conservation actions.

We have benefitted from the skills of a visiting researcher who has undertaken some GIS modelling of the Kielder area to assess the habitat suitability and likely use of the landscape by grey squirrels. This analysis, using least cost pathways methodologies will allow evaluation of the early warning camera trap network that has been implemented under conservation action C3.

SUMMARY OF D3 OBJECTIVES AND PROGRESS

OVERVIEW OF ANALYTICAL APPROACHES TO EVALUATE CONSERVATION ACTIONS

EVALUATING THE IMPLEMENTATION OF GREY SQUIRREL MANAGEMENT

PROVIDING AN ECOSYSTEM RESTORATION ASSESSMENT FOR PROJECT AREAS

SIMULATION MODEL OF ECOLOGICAL PROCESSES

LEAST COST PATHWAY PRELIMINARY ANALYSIS

Next Steps

Appendix: Software and Metadata references

SUMMARY OF D3 OBJECTIVES AND PROGRESS

Objectives and Progress

There are two main areas of work being coordinated and assessed by NU within Action D3: Ecosystem function restoration assessment, both of which evaluate data from Conservation Actions C1- C4.

Evaluate and inform the implementation of grey squirrel management

This action will 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 to 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 of this action 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 planned to 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 aimed be used to inform real time management actions and costed future management scenarios.

Progress of Action D3 in Year 2

Current status within global modelling framework

The global modelling framework was set out in the Prep Action A6 Report and is summarised in Table 1. Step 1 (Assemble Data) was completed during Prep Action A6. Steps 2 (standardize datasets) and 3 (develop model structure) 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 frequent data reporting (Step 2) is required to assess the ongoing control (Step 4).

Table 1: Global modelling framework.

1. Assemble data	2. Standardize datasets	3. Develop model structure	4. Assess impact of control	5. Rerun, update	6. Transfer, replicate
Review data, identify strengths and weaknesses, and develop methods to address objectives for each site.	Determine specific requirements for data collection with regards to environmental factors and control effort, produce data accordingly.	Occupancy models, removal data models, cost-benefit models.	Models progressively improved by adjusting for natural and site-specific variations with increasing amount of high quality data.	Update models using high quality data, produce more precise inferences.	High quality data representative of natural variations and control effort allow transferring inferences from conservation actions to other areas.

Progress in Year 1

Preparatory Action A6 (Nov 2015 to Aug 2016) highlighted that the analysis of field data to evaluate RSU actions in real time is dependent on the provision of sufficient, high quality data. The analytical demands of the RSU objectives include systematic records of operational effort in time and space, to be collected during the conservation actions of C1-C4. To achieve this the majority of Post-doctoral research time in year 1 (Sep 2016 to Aug 2017) was spent developing robust data recording mechanisms with all partners and working towards getting these implemented correctly.

Data provision in Year 1 was poor and objectives were set to improve this. The completion of the recording templates was raised at the Project Management Board in September 2017 and the regular provision of data was added to the RSU Project Management Board Risk Register.

Progress in Year 2

Data across the conservation actions C1 – C4 were analysed to determine patterns and trends relevant to the modelling framework. Each of the four conservation actions implement different control strategies, determined by the landscape features and the density and distribution of grey squirrels. The model assumptions have been explored in detail to determine the impact of season on parameters such as probability of detection and to better understand confounding of environmental and management variables.

We have also developed a simulation model to improve inference about different control strategies and their effectiveness.

We have been using GIS modelling approaches to model species distribution and likely corridor networks with the aim of informing future monitoring, surveillance strategies in Kielder forest and management.

Data provision remained the biggest challenge to progress with Action D3. The quantity and quality of data and frequency of reporting impacted on the modelling and evaluation in Year 2 (Sept 2017- Aug 2018) through both lack of time to complete the analysis (as time has been spent on data cleaning) and through recording errors which prevent some data from being used.

As a consequence, the ambition to inform real time management through modelling outputs has not been possible within the project. We aim to evaluate the conservation actions to inform future IAS management.

The objectives set by NU at the end of Year 1 are compared against the status at the end of Year 2 (Aug 2018) in Table 2.

Table 2: NU objectives set at the end of Year 1, to be completed during Year 2.

1. Finalise data recording templates to enable data quality and flow required for modelling **Actions:** NU to have meetings and site visits with RSU partners to discuss data recording and communications. Data recording templates to be updated to include tissue sampling records and related data. **Outcomes:** Meetings and site visits were with project partners helped resolve some data recording issues. Communication between partners remains unsatisfactory to resolve issues quickly. Data recording templates have been finalised. Data provision and checking still remain as issues causing delays to the project progress.	2. **Model development**. **Actions:** To develop models and investigate relevant temporal and spatial scales for modelling. To communicate with partners on how to use the model-based approach to inform management planning To identify best methods for communicating findings with partners (what is useful to each) **Outcomes:** NU have developed a simulation model which can be used to investigate the different temporal and spatial scales of analysis. Project data are not yet suitable for this task. Informing management planning is not feasible within the project timeframe due to the timing and quality of data provisions NU investigated useful ways to compare and contrast the effort data available. NU produced preliminary outputs which illustrate several aspects of the different management strategies and stages of eradication between partners. (Presented at NeoBiota Conference, Dun Laghoire, Ireland Sept 2018)

3. Least cost pathways modelling **Actions:** NU to host a funded research associate (Simone Caruso) to develop a GIS based model to link habitat suitability with the early warning system development for NWT **Outcomes:** Spatial models of Habitat suitability and species distributions have been used to generate modelled Least Cost Pathway maps for red and grey squirrels in the NWT project area. These models will now be used to provide recommendations for management planning and review of the early warning system surveillance and monitoring.

Ecological models, assumptions and requirements

The role, assumptions and requirements of ecological modelling to evaluate aspects of the conservation actions specific to the RSU objectives were investigated and described in detail in the first year review document titled *D3 – Ecosystem function restoration assessment: Outcomes of monitoring evaluations on all year 1 conservation actions* produced by NU in October 2017.

Ecological models allow the integration of multiple types and scales of data to investigate and understand the dynamics of complex ecological systems. We use models to improve our understanding of the changes in grey squirrel populations brought about by culling and the consequent impact on red squirrels.

Squirrel count data (*e.g.* numbers observed or captured) can be used to gather information about their overall abundance (given that we can't accurately count them all). However, in order to consider count data as an index of abundance and to investigate changes in abundance 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 areas practices, protocols and priorities vary.

Instead, count data must be standardised according to the methodology used to obtain the data (e.g. observation or trapping). The effort involved in data collection must be also be described precisely in time and space, so that count data can be adjusted to reflect differences between methods.

2. We have a good estimate of the probability of detection

Whatever method we use to count squirrels, e.g. sighting or captures, will not be completely accurate. In our models we also need to estimate the abundance of animals that are not observed or captured. To do this we assess the probability that we will detect an animal using a given methodology. The probability of detection will vary with habitat and through time and with variation in management practises (e.g. the use of baiting) and these factors need to be recorded so they can be used in the models.

The systematic and accurate recording of effort in space and time is essential for developing models.

Simulation model of ecological processes

The development of ecological models has been limited by the speed of data provision and the small size of the data set collated to date leading to confounding of ecological processes and management measures that are hard to separate analytically. In order to estimate the impact and effectiveness of management actions without observational data a simulation approach can be used. The ecology and abundance of squirrel populations can be simulated within a pre-determined landscape, as a response to natural variations and simulated control operations according to scenarios of interest, and the effect of control strategies to be assessed. The structure of ecological models is developed based on assumptions and parameters that describe underlying ecological processes, such as population dynamics and the interaction with habitat. It is anticipated that the simulated data may provide valuable insight about processes relevant to the modelling that are not explicitly captured in the recorded data.

The objectives are to 1) Use the simulation model to output data to replicate strategies in the RSU project. 2) To use the generated data to test the occupancy and removal models developed for the project. 3) Use the simulation model to test a range of management scenarios.

Least cost pathways assessment of Early Warning system

An early warning system has been implemented by NWT across Kielder Forest as part of Conservation Action C3. This is a network of fifty camera traps checked on a quarterly basis with the aim of monitoring the presence the red squirrel population and to detect new invasions of grey squirrels at an early stage.

To evaluate the spatial configuration of the camera network, we used a modelling, data driven approach. The purpose is to determine if the network is optimised for detection of invading grey squirrels but also to identify, analytically, the key areas that can be safeguarded from invasions, and in which red squirrel conservation efforts can be focused.

Data Provision

Data recorded to September 2018 using the project protocols are summarised in Table 3, these are the data NU are able to report on for the Year 2 conservation actions. Across the project data provision has not been at a rate to allow real-time modelling and subsequent feedback to inform management. Additional data submitted since February/March 2018 has not yet been fully checked/corrected by partners, preventing the data from being analysed.

Table 3: Summary of data reported in the agreed format to NU by partners, by end September 2018.

		NWT	LWT	UWT	RSTW
Data collection period	*Start date*	2016-12-01	2017-01-03	2017-06-26	2016-01-07
	End date	2018-03-30	2018-02-26	2018-02-27	2018-03-07
	Duration	~14.4 months	~13.8 months	~8months	~26months
Grey squirrel	*Total killed*	624	236	158	4017
	Total seen	130	130	0	0
Red squirrel	*Total recorded*	106	69	0	72
Sessions	*Total*	759	142	116	1517
	Control	518	142	116	1517
	Monitoring	243	0	0	0
Methods used	*Camera*	210	0	0	0
	Feeder	20	0	0	0
	Shoot	355	24	67	3
	Sighting	8	0	0	0

Trap	162	118	49	1514

Data recorded have mostly been reporting control sessions (shooting and trapping). RSU partners have captured and dispatched over five thousand grey squirrels since the start of the RSU project.

EVALUATING THE IMPLEMENTATION OF GREY SQUIRREL MANAGEMENT

The aim of this action is to use data collated on grey squirrel control to assess current control practices with the aim of optimising control in time and space, to 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 of this action 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.

Rates of grey squirrel removal per unit control effort through time

We have assessed the conservation action data to date by comparing grey squirrel removal rates through time. Modelling the effect of management interventions has not yet been possible, we report on the analysis to date. We report how the grey squirrel data provided can be used to evaluate different control strategies and inform future grey squirrel management beyond the RSU project and more generally for IAS management.

Quantifying control effort

To assess potential changes in the number of grey squirrel captures, either between project areas or through time data must be standardised to account for differences in management practise. We report removal data as the rate of grey squirrel removal per unit control effort. Effort in the RSU project is measured as:

- number of traps that were used

  Resource allocation is an important part of control management decisions and limitations and include the number of traps in use. Partners are required to provide the total number of traps involved in each trapping session.
- number of times traps were set daily

  Live traps may be set and/or checked once or twice daily. This practice is more often followed in woodlands where red squirrel can be found but it varies between partners, with the operator and throughout the year.
- total session duration

  Sessions are defined as consecutive days during which a given control method is undertaken by a given operator at a given site. The total number of days is the session duration. Time is an important factor for resource management decisions.

- control area

  All trap locations are recorded regardless whether they resulted in a capture or not, to allow an estimate of the effective trapping area covered during a session. A comparable similar metric is used to assess the area covered during shooting operations.

Data cleaning, assumptions and limitations

Records submitted without effort data cannot be used in the models as grey squirrel removal rates (per control unit effort) cannot be determined.

To include as much data in the analysis as possible we made the following assumptions.

- RSTW trap checks occur once daily
- RSTW maintains constant trapping area and intensity within woodlands on repeat sessions (trap number and location does not vary)
- Where individual records do not feature in session data:
  - captures recorded on consecutive days within a woodland form part of a session
  - the highest count of daily captures amongst those days is the total number of traps used for the session
  - the difference between the earliest and latest day is the session duration
- UWT trapping sessions are assimilable to point data (single or high density of traps over a reduced area)
- UWT maintains constant trapping area within woodlands (trap number and location does not vary)

These assumptions can introduce bias and limit the resolution of the analysis.

The information about each trapping session is essential to assess trapping efficiency. This information not only provides data on the trapping intensity but also on other key features such as checking and re-setting traps twice daily implies different trapping conditions (night and day) and resource allocation (rangers' time).

In some cases the number of captures recorded in a day is greater than the number of trapping occasions reported, which is not possible. To allow the data to be used in this analysis we have assumed that in these instances the number of trap checks was twice daily, but this suggests there is a recording error that may persist within the datasets. As this error and cannot be detected and corrected for records with fewer captures than traps, if this error exists we may be overestimating trapping success.

Units used to compute rates

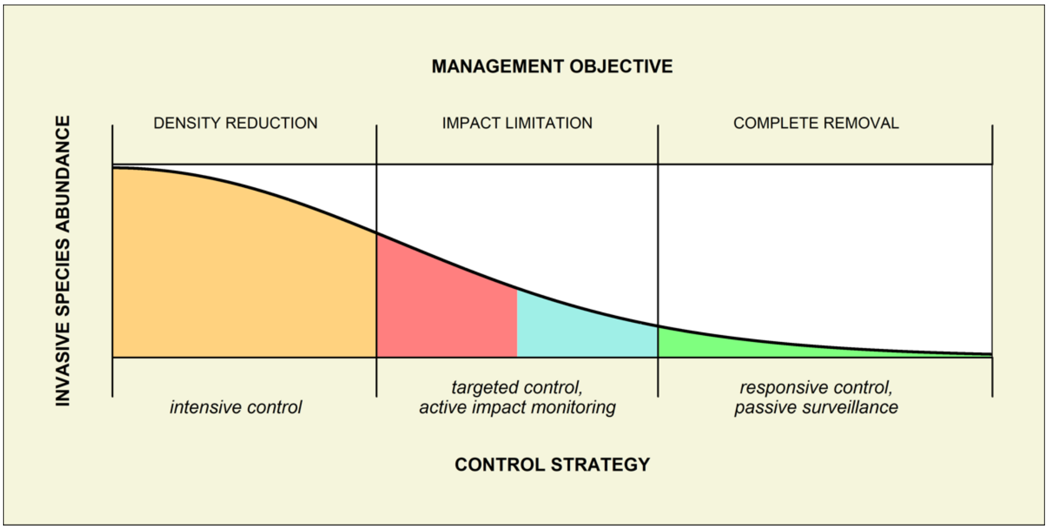
For trapping operations, the rate of grey squirrel captures per unit control effort is computed as the ratio of the total number of captures over the total number of trapping occasions, also referred to as traps*days (*i.e.* the number of times the traps were set daily, multiplied by the number of days the traps were set for, multiplied by the number of traps set):

$$\text{CPUE} = \frac{\text{Total number of captures daily}}{\text{Total number of traps set} * \text{Number of times traps were set daily}}$$

For shooting operations, the rate is computed as the ratio of the total number of captures over the total number of days multiplied by the number of shooters. For both rates, all variables may be aggregated at a similar time scale of interest, so that rates may be investigated as weekly, monthly and quarterly averages.

Stage of eradication and patterns in grey squirrel removal rates

RSU conservation actions differ in their grey squirrel management objectives and strategies reflecting the size, scale and configuration of the local landscape and abundance and distribution of red and grey squirrels. This can be compared to the different stages of invasive species control. In control programmes, management objectives fall into 3 main categories, each with a different control strategy:



- Density reduction: as many animals are removed as possible
- Impact limitation: removal to a density or area to contain impact, and monitoring of impact
- Complete removal from an area

The relationship between the management objectives and the effort involved in control operations is illustrated in Figure 1 and Figure 2 for all conservation actions, each dot represents a trapping session (period of continuous trapping).

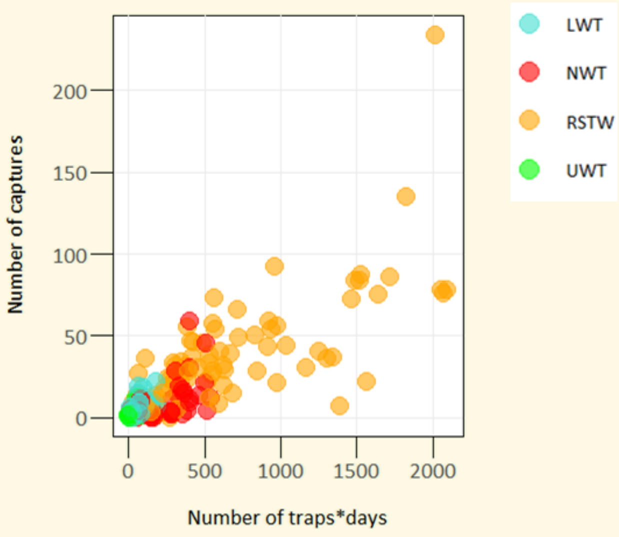


Figure 1: Rate of Grey Squirrel captures in relation to control effort as traps*days.

RSTW are typically dealing with a high density of grey squirrels. The control strategy involves a complete range of traps*days and area covered, compared with UWT where the density is low and the trapping strategy covers a much smaller area.

NWT have an impact limitation strategy, initial grey squirrel densities are likely lower and NWT also undertake monitoring operations using camera traps. For LWT the suitable habitat landscape is patchy, which present different implications as grey squirrels may be isolated or contained.

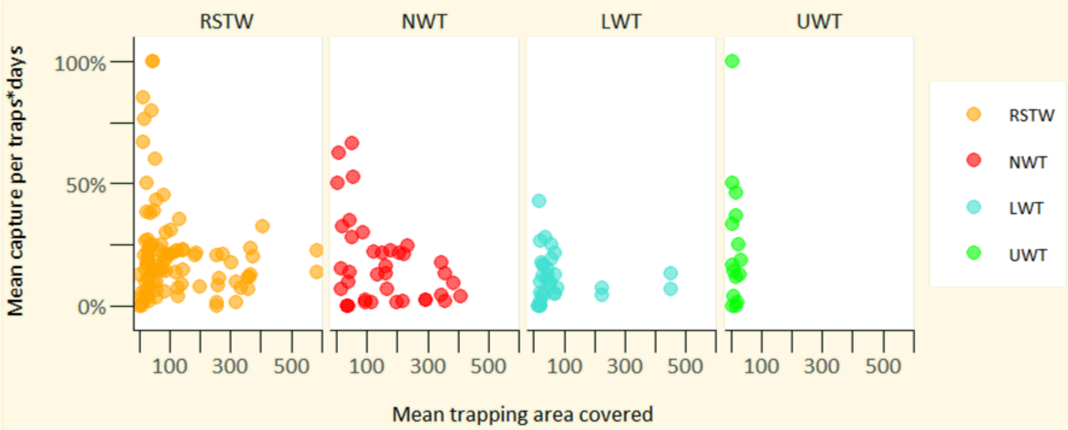


Figure 2: Rate of grey squirrel removal per unit control effort (traps*days).

Patterns through time since start of RSU data collection

Rates of grey squirrel removal per unit control effort were computed using the summary data for each trapping session provided by RSU partners for all the conservation actions up to September 2018. Data are presented separately for trapping operations (Figure 3) and shooting operations (Figure 4). Rates are presented at three timescales: weekly (a), monthly (b), and quarterly (c).

Assessment of grey squirrel populations should take account of changes through time relating to the animal, the landscape and the control operations. Squirrel populations undergo seasonal changes e.g. breeding and dispersal and may be influenced by climate and food availability while the design of control operations may combine an annual time frame (e.g. seasonal changes in methods and methodologies) with short-term demands and resources (e.g. staff availability).

Partners tend to use shooting and trapping methods depending on their expected efficiency throughout the year. There may be seasonality in the trend of rates of grey squirrel removal per trapping unit effort (traps * days, Figure 3) with a relative increase in trapping success towards the middle of the year. NU aim to test this hypothesis when more data are available.

Removal data recorded for shooting operations (Figure 4) have been more challenging to interpret and require a more complete and precise quantification of effort by partners to determine both the duration of sessions and the effective control area.

(a)

(b)

(c)

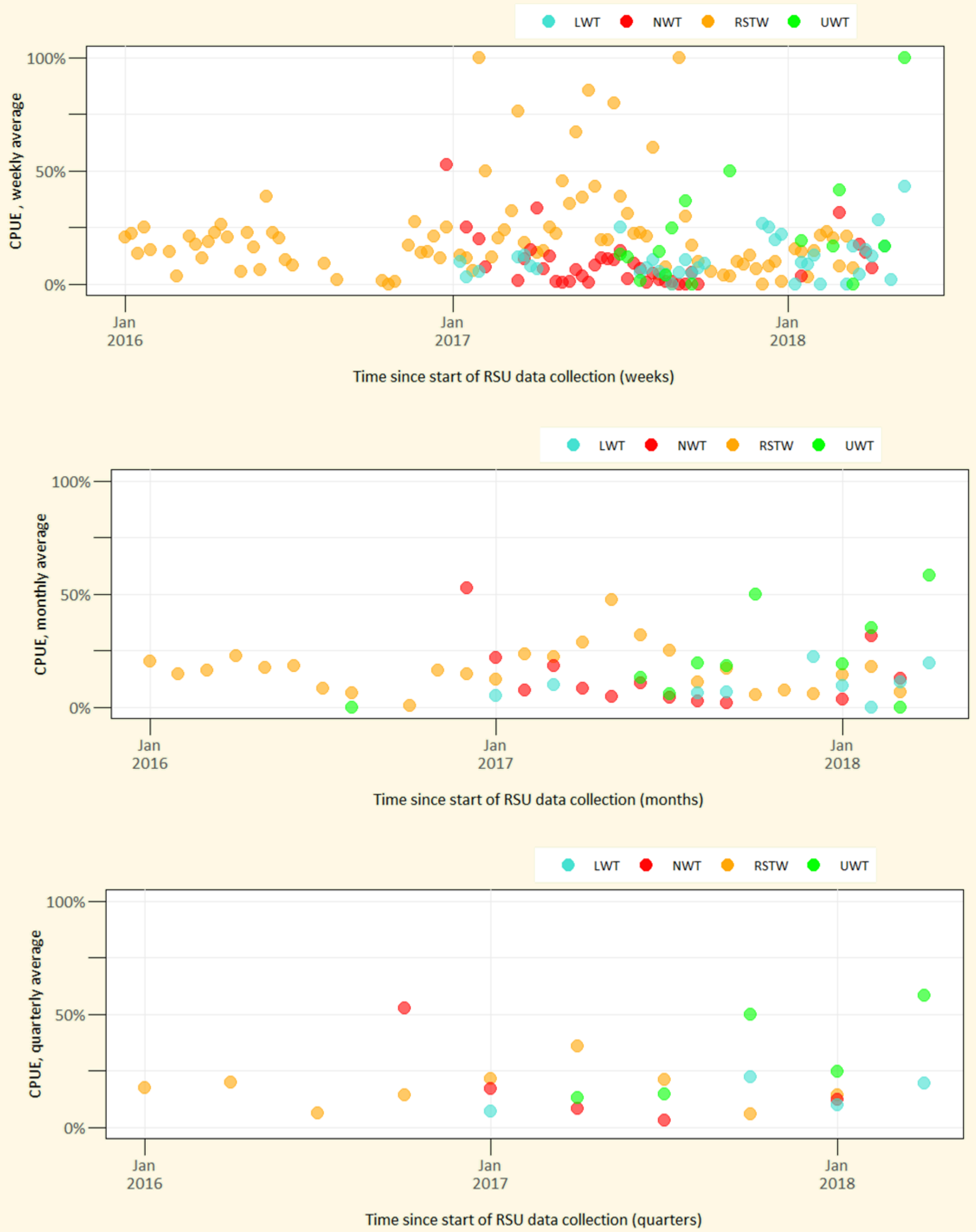


Figure 3: Rates of Grey Squirrel removal by trapping per unit effort as (a) a weekly average, (b) a monthly average, (c) a quarterly average, for all RSU partners since the start of RSU data collection.

The unit effort considered here is number of traps * number of days * number of times set daily.

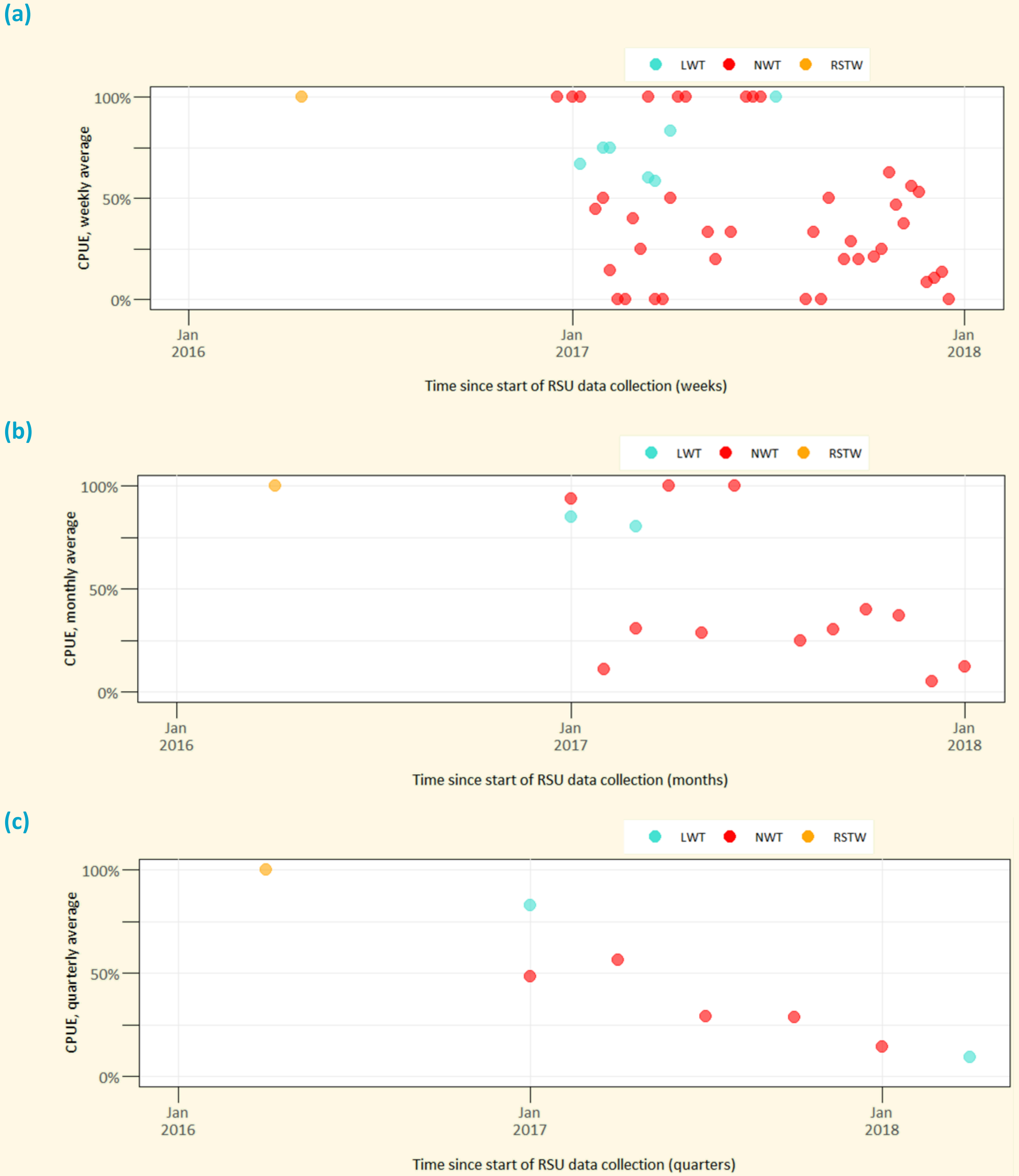


Figure 4: Rates of Grey Squirrel removal by shooting per shoot day as (a) a weekly average, (b) a monthly average, (c) a quarterly average, for all RSU partners since the start of RSU data collection.

The unit effort considered here is a day shooting (roaming, as opposed to shooting at feeder).

Patterns within trapping session duration

One assumption of modelling population abundance from capture data is that the probability of capture decreases each day of a control session (*i.e.* from Day 1 to Day 11 on Figure 5). As individuals captured are removed each day, they cannot be captured again nor are they replaced (assumption of closed population). As a result, the probability of capturing a grey squirrel must decrease each day within a session. This is a key assumption that allows captures to be linked to the size population.

To illustrate daily capture rates (Figure 5), squirrel capture records were summarised per day within each trapping session and matched with session level effort variables (number of traps and number of times traps were set daily). Only sessions with at least one successful trap were included in Figure 5.

Trapping success appears to decrease within the session for all partners. However, Figure 5 highlights two data recording issues that need to be investigated (1) the session duration for RSTW partners appears higher than expected (up to 10 days against an expected 5 days duration suggests recording errors) (2) the trapping success for NWT appears to be a maximum of 50% (suggesting a variable may be mis-recorded systematically).

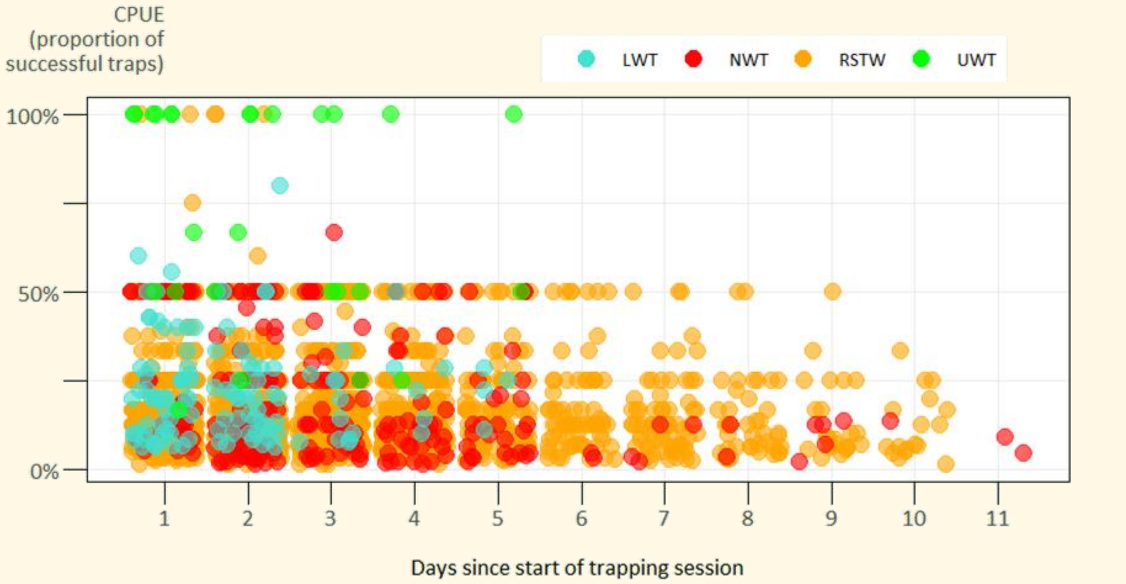


Figure 5: Daily proportion of successful traps since start of trapping session, for all partners.

Analytical approach: removal models

The effect of management interventions on grey squirrel populations can be modelled using removal models. A removal model is a hierarchical approach that models counts of captures as a response variable to investigate the population dynamics of populations under control. The models also consider our ability to detect and capture the squirrels given they are present in the landscape. The models are complex in that each level considered within the process (including detection, occupancy, availability, capture) has a set of specific assumptions and parameters.

One challenging step of the model estimation is the probability of detecting an individual.

The probability of detecting a grey squirrel at a site is affected by (1) the sampling method used, (2) a set of environmental variables characteristic to the site (3) the effort involved. Those factors also vary throughout the year. For instance, the probability of detecting a grey squirrel using a baited method may be more efficient at sites where the habitat is of poorer quality and at a time of year when animals are keen to forage. The probability that the animal will find the baited source is likely to increase after a few days. Additionally, the probability of detecting individuals decreases with population density.

The precision of these ecological models is dependent on the precision of the data used to develop them. The strategies in control interventions must be described with a level of precision that matches management decisions and allows detection of the effect of interest.

To date NU do not have sufficient data from the conservation actions to predict grey squirrel populations accurately using removal models. Of concern and further consideration are (1) that there is no quantifiable method to assess the incompleteness of the datasets (2) how the missing records impact the representativeness of the RSU data.

Factors affecting Grey Squirrel detection: control strategies

The RSU conservation actions include a range of control strategies that can be defined in terms of effort in space (area covered) and time (duration). The relationship between the area controlled and the control method through time is illustrated in Figure 6.

Due to the seasonal nature of trapping (spring-summer) and shooting (autumn-winter) there is a change in effective control area correlated with season, linked to these changes in management practise (Figure 6). As UWT partners are at a later stage of the grey squirrel eradication process, the typical control method is shooting at a feeder. The effective control area of this method is small, which we characterise as point data. In contrast, RSTW undertake control sessions using static trap locations within woodlands, here the effective control area is much larger. LWT and NWT use a combination of trapping and shooting operations. LWT shooting sessions are typically static, but NWT rangers cover more ground by shooting while roaming but the effective control area is smaller than those of trapping sessions.

Strategies also differ between across the conservation actions in terms of session duration (Figure 7). A typical trapping session is over the course of a five day working week with a two day break for the weekend. This is seen in the majority of the data provided by RSTW and NWT. RSTW records of trapping sessions greater than five days may represent two shorter sessions separated by a weekend that have been mis-recorded. NWT recorded a number of longer sessions at the beginning of the RSU project, which may reflect a change in strategy, in operator, or in control/recording habit. Longer

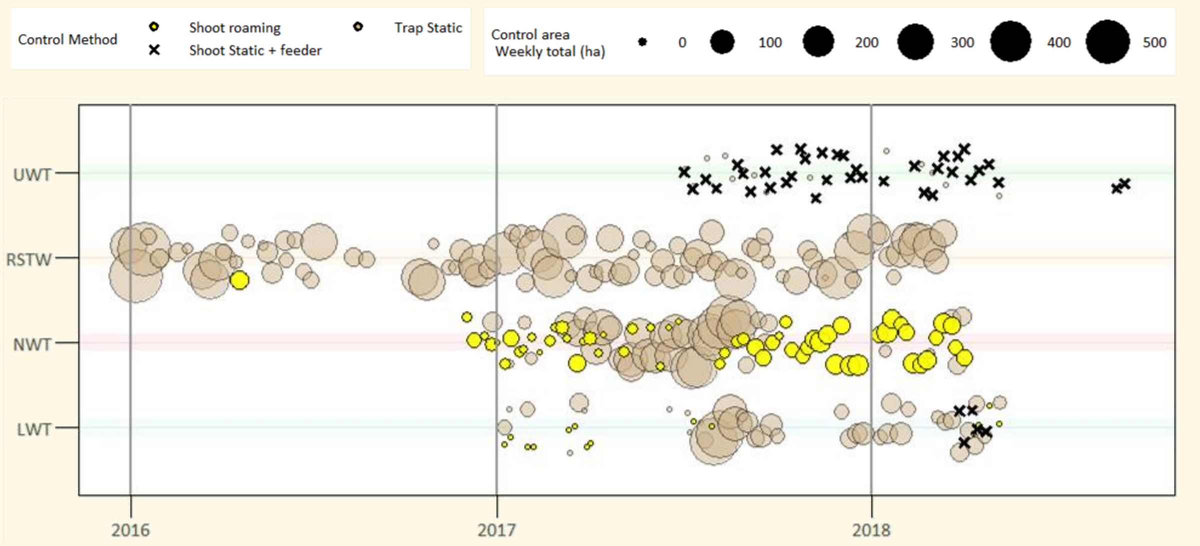


Figure 6: Average area covered weekly during sessions for three control method: shoot roaming, shoot at feeder, and trapping, by each partner since start of RSU data collection.

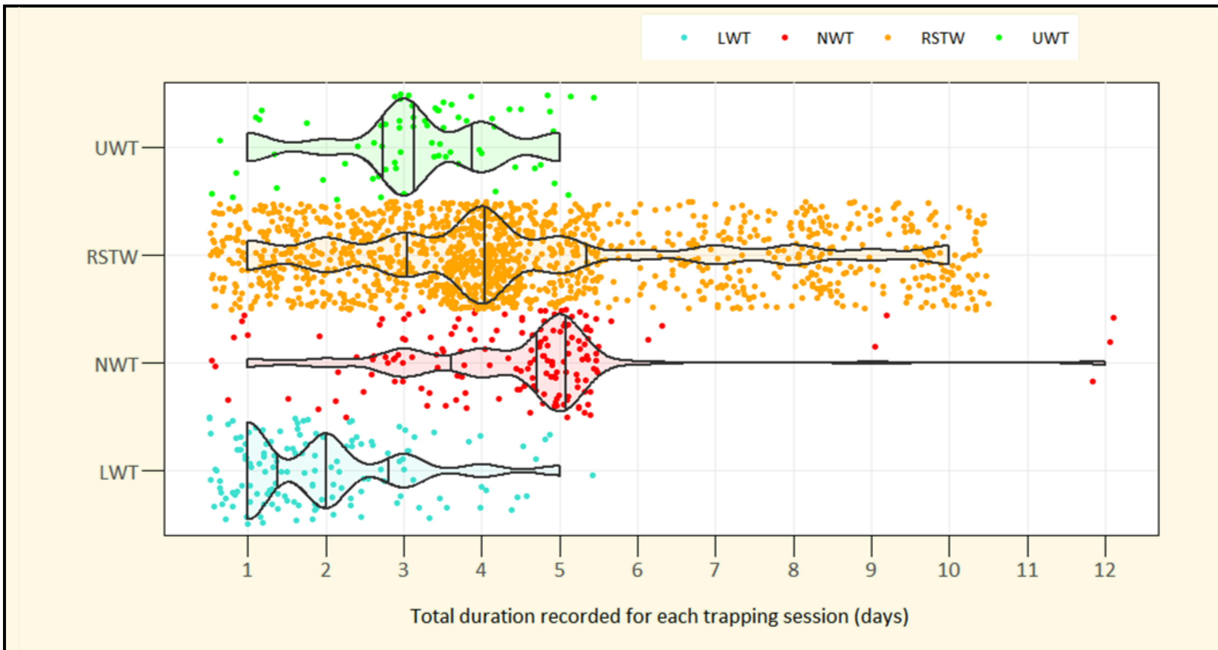


Figure 7: Duration of control sessions started weekly by each partner, including all data provided since start of RSU data collection.

trapping sessions are typically associated with areas of higher grey squirrel density and a less targeted control strategy approach than LWT and UWT partners.

Understanding the differences in control strategies is important when considering the assumptions associated with the probability of detection for the models. For example, with the current data from NWT it is difficult to attribute any change in probability of detection with season as there is also a distinct change in control method from trapping to shooting with season, confounding any association with one variable. With a larger data set it may be possible to understand and accurately account for this type of variation in the data.

PROVIDING 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 aimed to combine monitoring and control effort data to assess:

(3) change in abundance and range of native red squirrel in response to control
(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 aimed to be used to inform real time management actions and costed future management scenarios.

Change in abundance and range size of native Red Squirrel in response to control operations

Analytical approach: occupancy models

The change in abundance and range of the native red squirrel in response to culling of grey squirrels is assessed using occupancy modelling. Occupancy models can estimate the probability of red squirrel presence given particular environmental conditions, while accounting for imperfect detection (*i.e.* individuals may be present yet unseen).

Data requirements

Presence/absence data are systematically collected during quarterly early warning monitoring with camera traps by NWT partners. Red squirrel sightings are also recorded during any type of field visit (including all methods of control and monitoring), so the absence of a sighting during control operations can be assumed to be a record of non-detection.

The probability of detection may vary throughout the year, at different sites, and with specific sampling effort. As detection is imperfect, it is important to determine which environmental parameters influence the detection probability and in what way. However, it may also be that ranger behaviour/strategy is linked to red squirrel detection. Therefore, to investigate red squirrel detectability, data from multiple visits to sites, through different times of year and conditions are needed. Conservation action data are not yet extensive enough to fully explore the influence on detection probability.

Preliminary exploration of NWT data

Occupancy modelling will analyse presence/ absence data using an overlay of a 5km * 5km spatial grid over the RSU Kielder area. Quarterly monitoring surveys by NWT use trail cameras at fixed locations to monitor the presence of red and grey squirrels. Camera data and control records were summarised for each grid cell, each month to give a presence/absence record for the whole grid.

To calculate the probability of detecting a red squirrel given that the red squirrel is present, according to the methodological and environmental covariates we also need to assess the full range of effort and environmental data typical of the operations and landscape.

We explore the extent to which NWT records reflect the different sampling locations, ranger expertise, control strategies, and number of grey squirrel captures.

Factors affecting detection: Ranger and location

The probability of observing a red squirrel during a shooting session is likely to vary between rangers. Ideally this variation will not be systematic (e.g. reflective of different practices) as we will only learn about different rangers behaviour and be less able to associate changes in detection probability with landscape variables.

Four rangers have undertaken shooting operations at Kielder since the beginning of the RSU data collection. Records are mostly from two rangers ("Ranger C" undertook 125 shooting session and 190 for "Ranger M") and two other rangers undertook 40 sessions combined ("Ranger O"). Only three grid cells combine camera data, confirmed red squirrel record, and a visit by two rangers during shooting session (Figure 8), which might be expected as the rangers are assigned to different 'patches'. This limits the ability to estimate whether change in the probability of detection is ranger-specific, or site-specific.

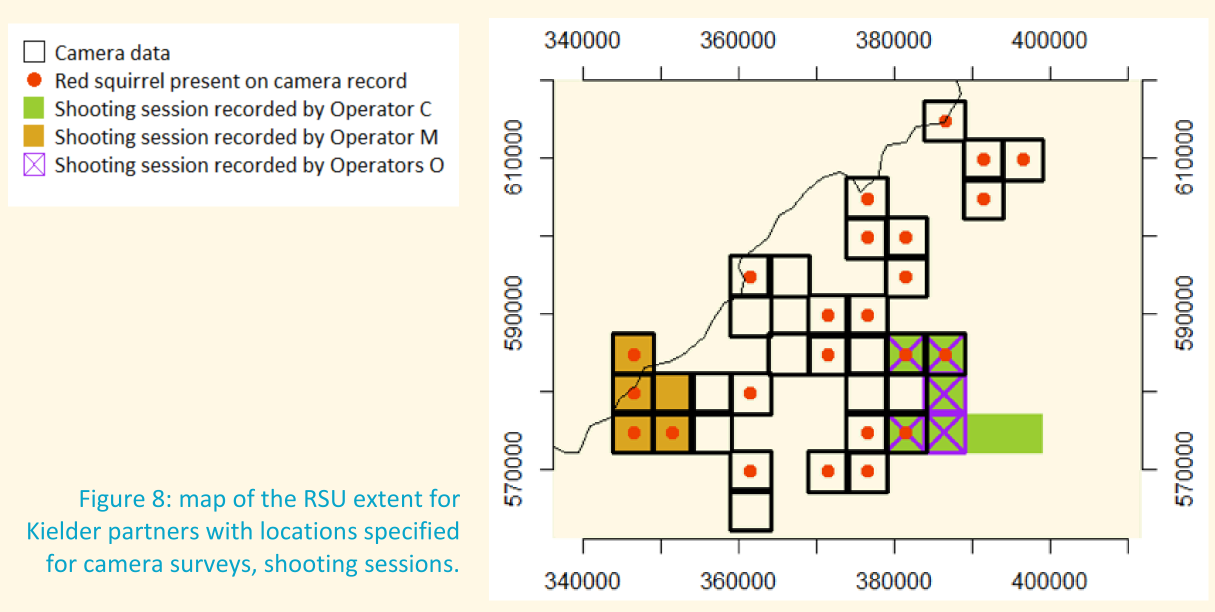


Figure 8: map of the RSU extent for Kielder partners with locations specified for camera surveys, shooting sessions.

Factors affecting detection: Strategies and Rangers

Visits by rangers M and O to the three cells combining red squirrel sighting camera record with shooting operations are separated by several months (Figure 9).

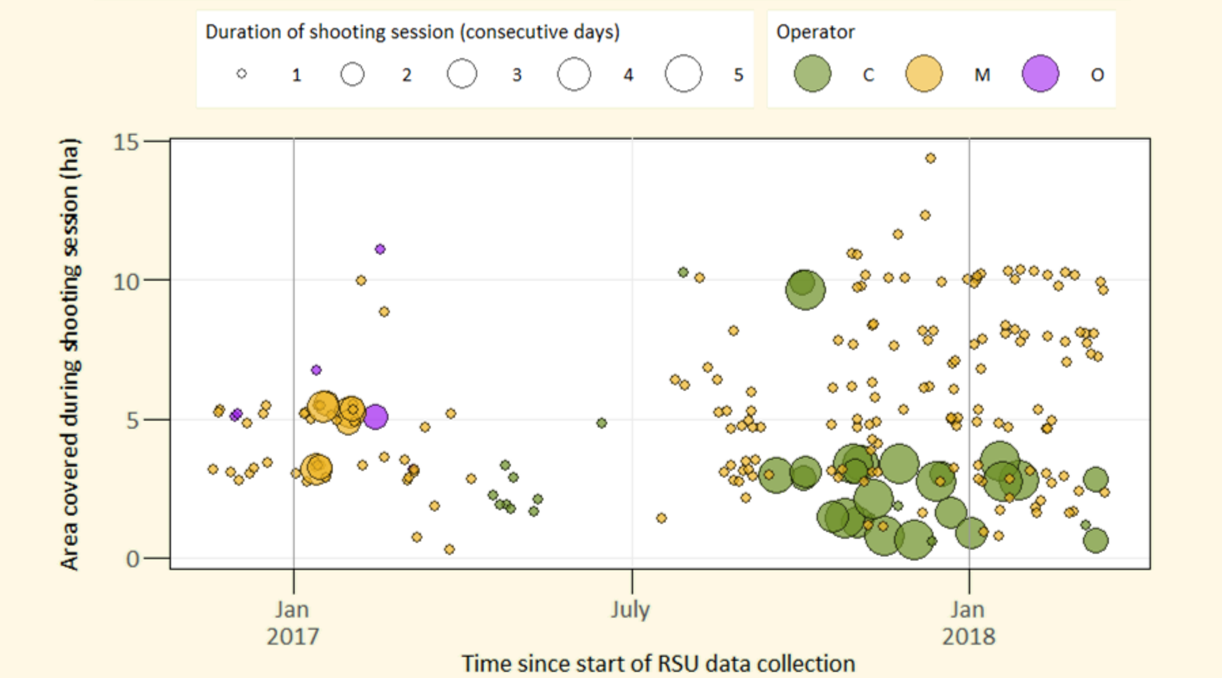


Figure 9: Area covered during a shooting session through since the start of the RSU data collection; by different rangers and for varying session durations.

Illustration of the area and duration of shooting sessions highlights that variation in strategies are highly ranger-specific (Figure 9). It appears ranger C tends to cover larger areas during shorter sessions, and ranger M tends to undertake shorter sessions but covers a broader area. It is also possible that this difference highlights an inconsistency in data recording for shooting, which has been a challenge across the whole project.

Systematic variation between rangers and through time confound the assessment of the effects of covariates (time of year, area and duration) and including them in an occupancy model may reflect ranger-specificity.

Factors affecting detection: Strategies and Grey Squirrel capture

The probability of detection of red squirrels may be influenced by a ranger detecting a grey squirrel (and subsequent focus on dispatch). We explore the effort devoted in time and space for the three operators, in situations when the grey squirrel was detected versus not (Figure 10).

We find that the control strategies do differ with the detection of grey squirrel. When grey squirrels

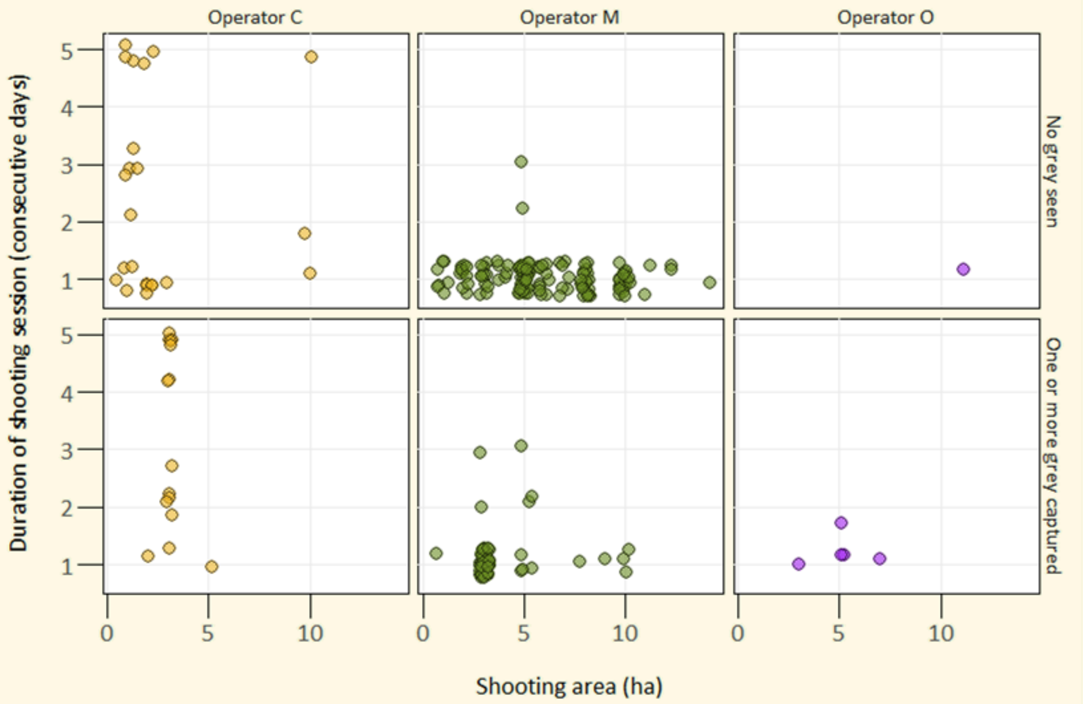


Figure 10: Variations in shooting effort for different operators, when grey squirrels are detected or not.

are present, Ranger C may cover more ground, while Ranger M is more likely to revisit a site for one or two consecutive days more than when no grey squirrel is detected (Figure 10). This is perhaps an expected management strategy to maximise control effort, but the lack of consistency of control strategy confounds our ability to separate the reason for a change in probability of detection.

Impact of management on the proportion of grey squirrels carrying infections

RSU Disease monitoring objectives

1. To quantify the impact of culling upon two types of viral infections which threaten native red squirrels.
2. To create a tissue sample archive that will facilitate future and retrospective investigations
3. To provide prescriptive and evidence-based assessments of the impact of culling upon pathogenic and asymptomatic infections carried by grey squirrels. These will factor in landscape permeability and will help evolve IAS management by advancing our understanding of the full spectrum of impacts that such species have on regional native ecosystems.

Developments to date

To determine the feasibility of objective 1 NU conducted a modelling simulation and power analysis to determine the level of testing (number of individual tissue samples) required to detect a decline in prevalence of SQPV and adenovirus antibodies in through time. Testing of spleen and blood were expected to be the tissues used for antibody detection. The power analysis, based on the current sensitivity of the viral testing, showed that the number of individual squirrel samples needed will vary depending on the initial disease prevalence, this is likely to be between 40 and 80 samples per year (per conservation action).

Ulster, Gwynedd, Merseyside and Kielder project areas are all routinely collecting tissue samples, fulfilling objective 2.

APHA, the preferred laboratory for the tissue testing, have now developed new tests for Adenovirus and SQPV, using hair and whisker samples. If these are more sensitive further power analysis modelling will be required to determine sample numbers required to detect change.

HYPOTHESES AND TESTING SCENARIOS.

Prevalence of disease in grey squirrels declines in areas as intensive culling occurs.

This builds on the Angelsey work where a decline in serprevalence during grey eradication was observed. RSU could carry out a ‘repeat’ to determine if this decline is seen in other areas and at a finer landscape scale. To test this hypothesis samples will need to be from areas where intensive culling is occurring and documented. This may only be feasible for the Kielder and Gwynedd areas.

Reinvading/dispersing grey squirrels pose a greater disease risk than established populations.

To test this hypothesis we could use samples from each project area (but not necessarily the same number from all areas) to compare what we deem to be ‘established populations’ with the individuals reappearing after a significant culling event. We can test disease prevalence against a range of other variables such as time since woodland clear, distance to nearest known grey squirrel population, perhaps link into least cost pathways modelling (see Objective 3 above re. landscape permeability).

Proposed Options

1. Split samples equally between all partners. This tests no specific hypothesis, may not result in ability to may any robust conclusions.
2. Staged testing approach. Initially test samples (number to be defined) from each project area – this will give us a baseline to compare future samples to and inform our decision making as to which testing scenario (above) is best to follow.
3. Include analysis of alternate tissues - If we delay any testing until 2019 the new APHA method will have been further refined/ developed. If the sensitivity of these tests is better (and no more expensive) we may have more scope to test multiple/ different hypotheses. This is because fewer samples may be needed to detect a change in disease prevalence with a more sensitive test – we need further information to determine this.

SIMULATION MODEL OF ECOLOGICAL PROCESSES

OVERVIEW

A simulation model has been developed to estimate the impact and effectiveness of management actions where observational data are lacking or incomplete. This approach simulates the ecology and abundance of squirrel populations within a pre-determined landscape, the model can incorporate natural variations, such as season and response to management actions which allows the impact of control strategies to be assessed. The structure of ecological models is developed based on assumptions and parameters that describe underlying ecological processes, such as population dynamics and the interaction with habitat. It is anticipated that the simulated data may provide valuable insight about processes relevant to the modelling that are not explicitly captured in the recorded data.

The objectives are to 1) Use the simulation model to output data to replicate strategies in the RSU project. 2) To use the generated data to test the occupancy and removal models developed for the project. 3) Use the simulation model to test a range of management scenarios.

MODEL DESIGN

The simulation design consists of four interacting subsystems specified within a determined spatial domain, namely the Grey Squirrel population dynamics, the environmental dynamics, the control dynamics, and the economics.

Spatial domain

The spatial domain describes the layout of hypothetical woodlands within a determined area and may accommodate a range of designs. Parameters of interest to generate the layout include the position, shape, size, number, and isolation (illustrated on Figure 11).

Woodlands are initially described using sites variables such as the proportion of broadleaved, coniferous or grassland habitats cover within the woodland (for instance, as on Figure 12). Any site parameters known to influence the carrying capacity of the woodland for Grey Squirrel occupancy can be incorporated.

The simulation design consists of four interacting subsystems specified within a determined spatial domain, namely the Grey Squirrel population dynamics, the environmental dynamics, the control dynamics, and the economics.

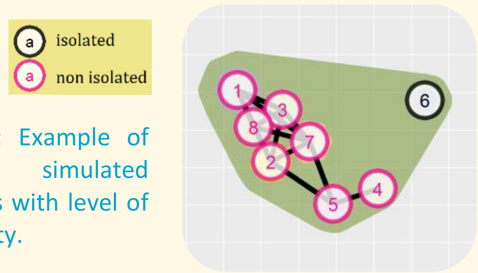


Figure 11: Example of eight simulated woodlands with level of connectivity.

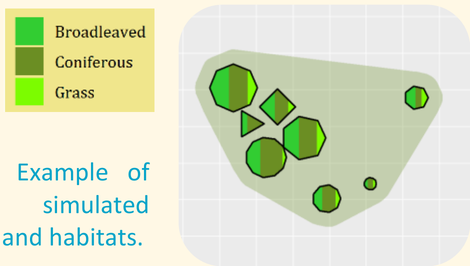


Figure 12: Example of eight simulated woodlands and habitats.

Grey squirrel population dynamics

Mathematical models describing grey squirrel population dynamics may all be integrated within this sub-system with a chosen level of detail. The interaction of individuals with their environment may vary with habitat suitability, seasonal food resources, breeding season and any biometrics. Life stages include juveniles and adults with two sub-classes for females, who may breed once or twice a year depending on their age-class. Proportions of each demographics are computed as probabilities for the population, rather than at an individual level.

Environmental dynamics

The environment subsystem is described by variations specific to each woodland throughout the year. In the future, variables may include woodland productivity (mast) which may influence population growth, and rainfall which may affect detectability.

The main time-dependent variable is currently temperature. Monthly averages were retrieved (MetOffice data) for several locations in the UK, including the four RSU areas. The temperature on each day within each woodland is computed via interpolation within the temperature range of interest (Figure 13).

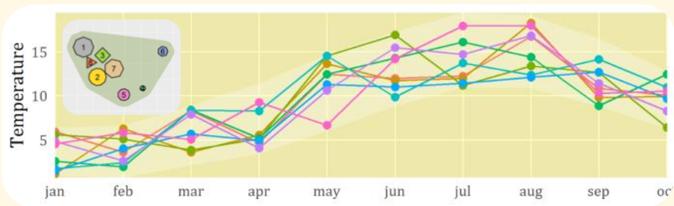


Figure 13: Example of simulated temperatures for sampling period Jan-Oct (monthly averages).

Control dynamics

Control methods can be trapping, shooting roaming or shooting at feeder. All types of methods are incorporated simultaneously within the simulation of control operations.

Methods are described using effort variables similar to those asked from partners for RSU data collection.

Effort variables include the area covered during a session, the trapping intensity, duration. The efficiency of each is related to the seasons in terms of detectability.

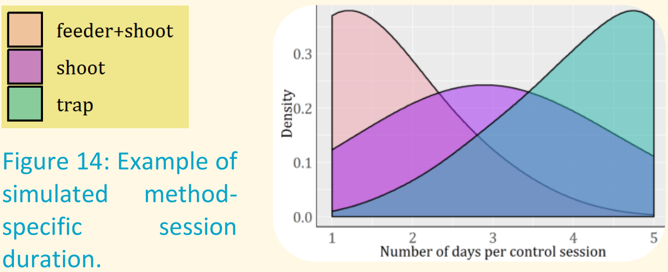


Figure 14: Example of simulated method-specific session duration.

Effort variables are method-specific and initialised using observations from RSU data, so that for instance the session duration tends to be longer for trapping than for shooting roaming or shooting at feeder (Figure 14).

Temporal patterns currently include random durations, repeated sampling and increasing or decreasing durations per woodland. By accounting for every aspect of the control effort, realistic strategies of any kind can be incorporated within the simulation.

Economics

By quantifying effort precisely, expenditures can be computed for the control operations for a given scenario. Variables of interest will include material (*e.g*. number of traps, bait) and time demands (*i.e.* ranger time). The figures used to estimate the costs associated with control operations may be adjusted to RSU partners when available.

Interactions

Interactions between the four subsystems are complex and change through time. Examples of interactions to be included in the simulation model include:

- Control operations affect the size of the population; population growth does not include the individuals removed.
- Detection of Grey Squirrels is influenced by the type of method and the time of year it is used. Baited methods are assumed less efficient when food is abundant (determined by the interaction of site and season).
- Movement between woodlands (immigration, emigration) is influenced by Grey Squirrel density and woodland connectivity, so that when the density nears the carrying capacity of a given woodland individuals redistribute between nearby woodlands in varying proportions and when possible.
- The availability of Grey Squirrels to be detected may vary with control method, effort, time of year and individuals (*e.g*. juveniles who will not travel far enough to reach the trap).
- The detection probability associated with each session is expressed as a function of control measures and vary seasonally and depending on the habitat (*e.g*. less visibility decreases shooting detection).

Model Duration and Outputs

Simulations can be designed to run and produce outcomes either for a finite period of time (*e.g*. a funding period), or until a specific event occurs *(e.g*. squirrel density becomes reduced below a pre-determined value), or an ecological threshold point or value of interest. Termination and threshold points are adaptable to the question of interest associated with each scenario.

For instance, a scenario may be concerned with the Grey Squirrel density in terms of the likely damage to wood bark; values may also be compared with literature data for principle validation (such as the average summer density to be expected). In this case the simulation outcome may be illustrated in relation to those values (Figure 15).

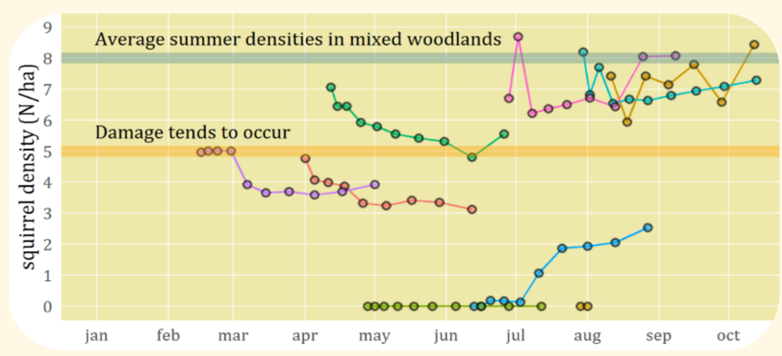


Figure 15: Example of simulation output: Variations in Grey Squirrel density for control Jan-Oct, per woodland.

An example of threshold value currently incorporated in the simulation is the carrying capacity associated with each woodland at a given time of year. When population density is near carrying capacity, the simulation is designed so that survival decreases, emigration increases, detectability and therefore captures increase, leading to an abrupt change in the population.

Further Modelling

The simulation model will be used to test a number of scenarios and hypothesis to better understand the different management objectives and strategies.

Overview and objectives

NWT partners have developed and implemented an early warning system across Kielder Forest in conservation Action C3. A network of fifty camera trap locations were chosen, based on expert opinion as the most suitable spacing and configuration, with the aim of monitoring the presence the red squirrel population and to detect new invasions of grey squirrels at an early stage.

To evaluate the spatial configuration of the camera network, we used a modelling, data driven approach. The Machine Learning approach (*i.e.*, MaxEnt algorithm), was used to determine if the network is optimised for detection of invading grey squirrels but also to identify analytically the key areas that can be safeguarded from invasions, and in which red squirrel conservation efforts can be focused.

Analytical approach

Modelling process

The modelling approach combining Species Distribution Models (SDM) and Least Cost Pathway (LCP) analysis was used to identify the most likely movement corridors for Grey Squirrel across the North of England landscape. A similar approach was used to inform grey squirrel control strategy in Northern Ireland for RSU (Flaherty and Lawton, 2016).

The modelling process was split in two steps. First, a Habitat Suitability Model (HSM) was created using MaxEnt (3.4.1) algorithm (Phillips *et al.*, 2006) and based on known squirrel sightings data, published demographic parameters and environmental variables. Second, the habitat suitability model was used to build a Least Cost Pathways model of landscape scale movement using the program UNICOR which can highlight spatial areas of high connectivity.

Data requirements

RSU data

Red and Grey occurrence records from the NWT RSNE annual monitoring system from January 2013 to March 2018, including all recording methods (camera traps, live trapping, shooting, hair tube, feeders, sightings) were used for the models. All data reported without a specified method were assumed to be a sighting. The original data hold records at different resolutions, ranging from 10m to 1 km. Presence only data was filtered to only include high resolution ≤ 25m occurrence records. A total of 649 presence records were used for the grey squirrel model.

Metadata

The UK Land Cover Map 2015 was downloaded from EDiNA web site https://digimap.edina.ac.uk/webhelp/environment/data_information/landcover_data.htm, which maps 21 classes of broad habitat and set a minimum mappable area of > 0.5 ha. So, parcels less than 0.5 ha and linear features less than 20m are dissolved into the surrounding landscape during the production process. Both vector and raster layers (at 25m resolution) were downloaded, and prepared in QGIS 2.16.2.

The altitude elevation layer was derived from SRTM (Shuttle Radar Topography Mission) 1 Arc-Second Global and downloaded from USGS web site https://earthexplorer.usgs.gov/. It was processed in QGIS at a resolution of 25m; the whole range of values (between 4 and 615 m.s.l.m) has been considered suitable for grey squirrel, so it was used by MaxEnt without any reclassification.

Habitat suitability model

MaxEnt is a general purpose machine-learning technique, which computes a habitat suitability model using presence-only data. The algorithm models the environmental characteristics of locations of species presence, such as landcover and altitude. All the default settings of the MaxEnt algorithm were maintained apart from the maximum interaction which was increased from 500 to 5000 to give the model the right time to converge and avoid over-prediction and / or under-prediction. True absence points are difficult to obtain in the field and MaxEnt has been developed to work on presence only data. A set of background data (pseudo-absence points) were sampled from the landscape (10,000 selected by default) to contrast environmental conditions at the background locations with those at observed presence locations. MaxEnt assumes that the species is equally likely to be anywhere on the landscape, so every pixel has the same probability of being selected as a background point. However, occurrence records are likely to reflect a sampling bias due to sampling effort being focused in suitable areas rather than randomly. This bias means that some environmental conditions are more frequently sampled the others, the MaxEnt program overcomes this with the use of a bias file in the model. The bias file was built using a Gaussian kernel density estimation with a standard deviation of 8km (maximum grey squirrel dispersal distance), scaling the resulting grid values to a range between 1 – 20, according to Elith *et al.*, 2010. In this way we can correct and reduce the sampling bias by forcing MaxEnt to choose the background data from within the area covered by bias file, giving the same sampling bias to both datasets. As affirmed by Phillips *et.*, al (2009) the hope is that a model based on biased presence data and background data with the same bias will not focus on the sample bias, but will focus on any differentiation between the distribution of the occurrences and that of the background. This procedure allows to improve the performance of the SDM.

A logistic output has been set in Maxent as attempt to get as close as possible to an estimate of the probability that a species is present in a given environment, so the final output returns a habitat suitability index (HSI), that is indicative of probability of presence, with a score ranging from 1 (high probability) to 0 (low / no probability) (Figure 16). Using a logistic output implies a strong assumption about tau (τ) or prevalence (the proportion of locality where the species occurs), arbitrary assuming to be 0.5 by default in MaxEnt. This can be risky if not related to biological justification, resulting in a huge impact on the predicted probability assigned to each location. According to Phillips and Dudik (2008), a default τ=0.5 can be interpreted as the probability of presence at "average" presence locations, and that logistic output can be interpreted as probability of presence. Model accuracy and its predictive power was evaluated using the Area Under the Curve (AUC). The AUC is a measure of model performance with score ranging from 0 to 1. A score of 0.5 means that the model is as good as random, while a score closer to 1 indicate better model performance (*i.e.*, correctly identify presence and absence). The AUC score for the final model, coming from an average of 10 replicates, was 0.821 (± 0.016 standard deviation) which indicates that grey squirrel presence was correctly predicted in 82.1% of cases. Grey squirrel occurrence records show positive correlation with woodland and suburban areas as expected, and negative association with landscape dominated by grasslands, agriculture, wetlands and water bodies.

The habitat suitability index derived from the MaxEnt output is inversely linked to the landscape resistance which is instrumental to developing least cost pathway models. The landscape resistance map is generated by computing the reciprocal cubic function of the habitat suitability index for each pixel, with the exception of value below 0.1 where a resistance score of 100,000 was applied; higher habitat suitability implies lower landscape resistance.

Least cost pathway

Least cost pathway models are tools to identify the mostly likely used routes between presence points across a landscape. UNICOR (Universal Corridor Network Simulator) (Landguth *et al.*, 2011) is a species connectivity and corridor identification tool whose output can be used to perform connectivity analysis by highlighting bottlenecks between locations and areas of high connectivity.

UNICOR is implemented in Python and uses Dijkstra's algorithm to compute a single path or all the shortest paths between points on a landscape map to create a connectivity graph. The landscape map is derived from a habitat suitability output where each pixel is given a weight (resistance value) which represent the "cost" of movement across that pixel. The connectivity graph is composed of multiple paths which each represent a likely corridor of movement with different strength depend on the cost of moving within the landscape through the resistance surface.

UNICOR requires two input file data: 1) a landscape resistance surface and 2) a point location, to search for paths between.

We used grey squirrel presence points as the point locations representing start and end points between paths. In order for UNICOR to model paths correctly, points need to fall in a unique pixel of the resistance surface, so, the starting number of presence records were filtered to remove overlapping points. To reduce the UNICOR running time we also limited the number of presence points to one per woodland patch, whereby these patches could be considered as the start and end points of the paths.

Preliminary outcomes

Habitat suitability model

The habitat suitability model for Grey Squirrel in Kielder Forest is illustrated on **Error! Reference ource not found.**. The Habitat Suitability Index (HSI) can be interpreted as probability of presence at "average" presence locations. Non-woodland areas and foresty blocks of sitka spruce had the lowest probability of presence.

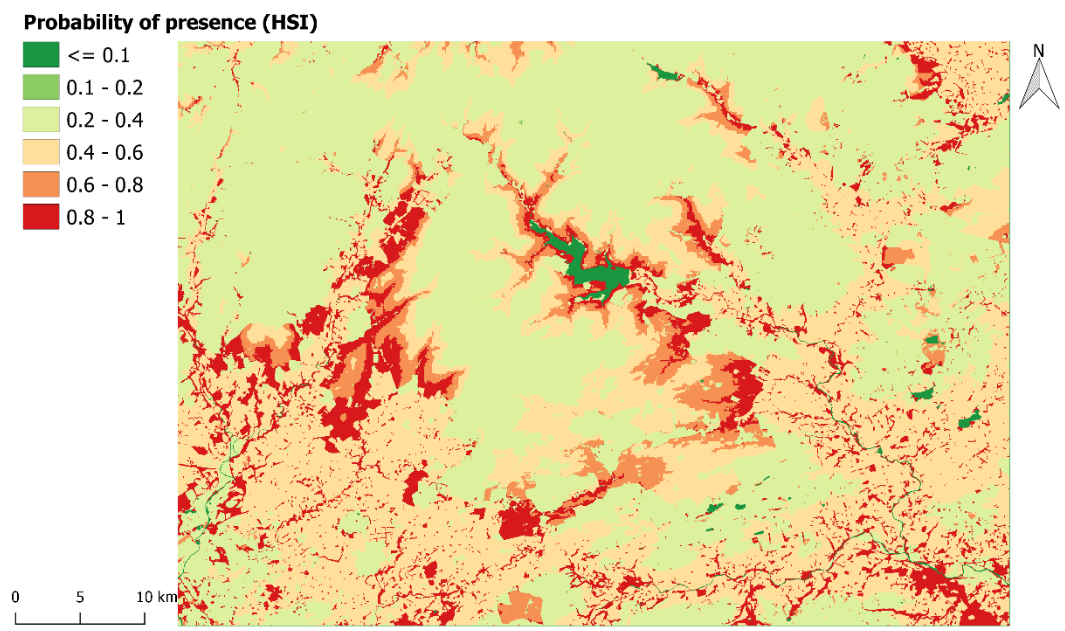


Figure 16 : Preliminary habitat suitability map for Grey Squirrel in Kielder Forest, 25m resolution

LEAST COST PATHWAY ANALYSIS

The habitat suitability index derived from MaxEnt was used to compute the landscape resistance map for each pixel of the RSU area of the Kielder Forest (Figure 16). Black lines show the whole network of least cost pathways of grey squirrel movements between the nodes, which are occurrence records of grey squirrels.

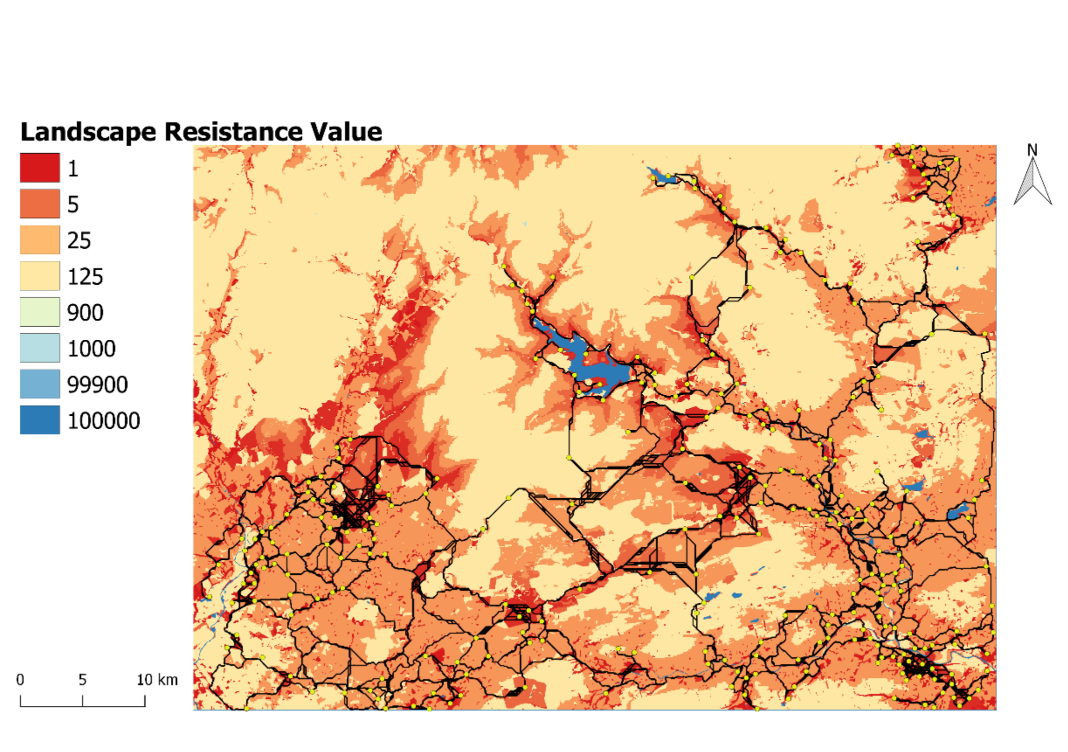


Figure 16: Preliminary landscape resistance surface map. Black lines indicate least cost pathways between nodes (yellow dots)

Bottlenecks between locations and areas of high connectivity for Grey Squirrel movement in the Kielder Forest are shown on **Error! Reference source not found.** and **Error! Reference source not und.**.

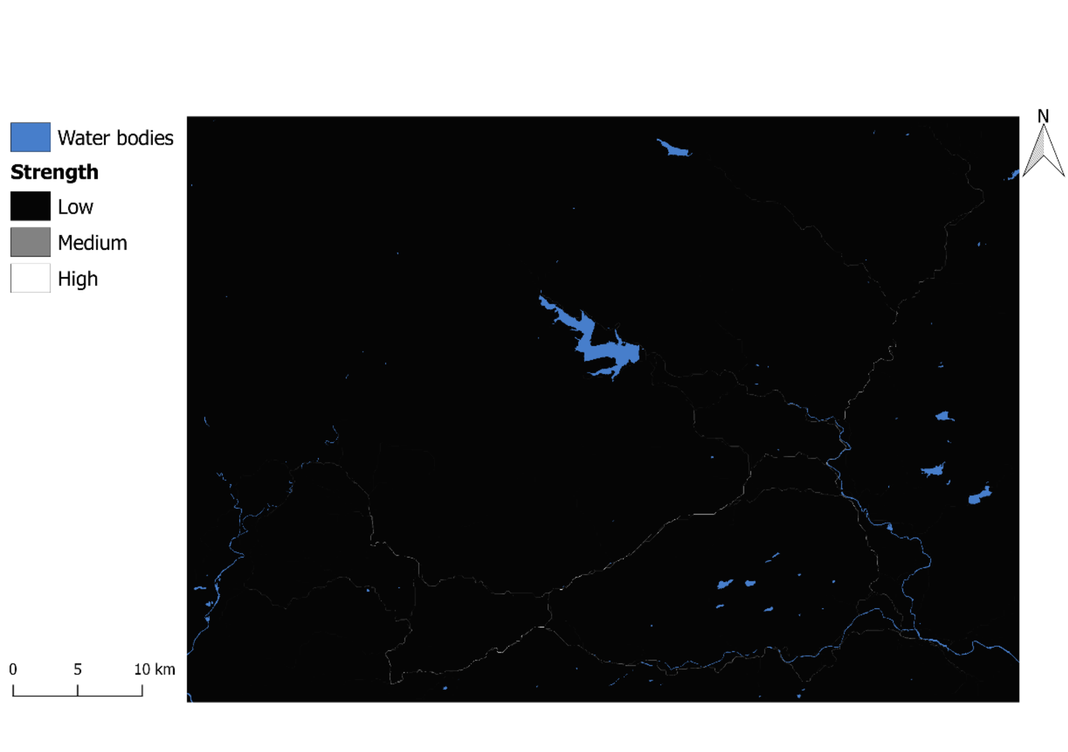


Figure 18: Estimated least cost corridors for Grey Squirrel in the Kielder Forest created using UNICOR

Error! Reference source not found. represent the strongest least costly connections, which connects he Southern part of Kielder Forest to the North, towards Northumberland National Park, and to the Western part, following the broadleaves woodlands along the two mains river valleys. The models outputs also highlight the crucial importance of broadleaves woodland in drive the grey squirrel movements into the landscape, suggesting that these areas represent key points which need to be monitored systematically to prevent further incursion and to protect red squirrel presence areas.

The whole network of pathways is clearly visible in **Error! Reference source not found.**. A Gaussian ernel density of 400m was applied to the connections network; this value has been shows to be the upper limit of the grey squirrel perceptual range, and represent their possible daily movements (Zollner, 2000; Mech & Zollner, 2002; Goheen *et al.*, 2003). This tool highlights the high connectivity areas, bottlenecks and eventually barriers that could potentially impede grey squirrel spread.

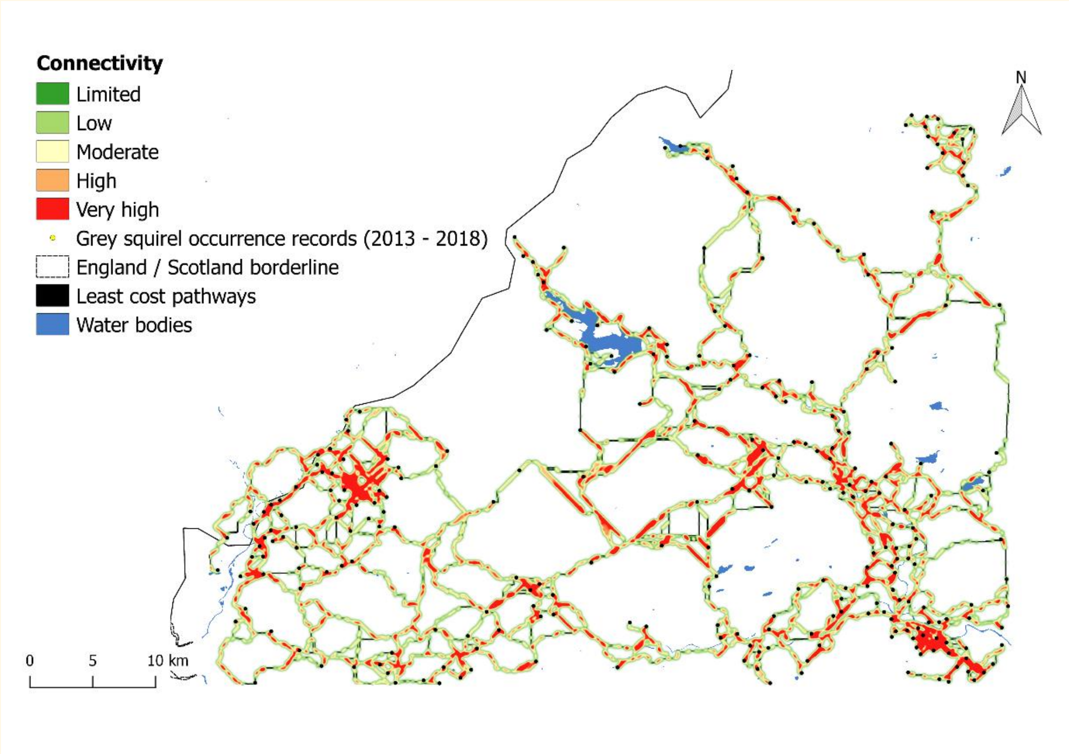


Figure 19: Predicted areas of high connectivity and bottlenecks following the application of a 400m Gaussian kernel density upon the least cost pathways network created by UNICOR

Areas highlighted in red and orange represent highest connections between nodes, which identify the strongest connectivity densities along the Wark river valley on the South and on the Western side of Kielder Forest (Kidland) up to the borderline with Scotland.

Further Modelling

One weakness of these models is that they are based on England grey squirrel data, but considering the key geographical position of Kielder Forest upon the borderline with Scotland, particular attention needs to be taken of squirrels to the north, that can be represent a potential source of new invaders. We are collaborating with Saving Scotland's Red Squirrels (SSRS) integrate data from across the Scottish border, the models will then be rerun to investigate dispersal from the north and from the south. The models will then be assessed in conjunction with the Early warning system that NWT have in place across the area to determine the optimal locations for camera traps.

NEXT STEPS

Objectives for year 3

1. *Evaluate conservation actions*
   Data provision remains key to being able to fully evaluate the conservation actions. NU will meet with all project partners, to obtain updates to the datasets for modelling, to ensure the datasets are as complete as possible. Data to date will be discussed and visualised.

2. *Using conservation data and simulation model output to determine effectiveness of different management approaches.*
   NU will use the collected data to model the impact of the conservation actions. The simulation model will be used to assess additional management scenarios. NU will obtain data on ranger costs to inform a cost effectiveness analysis.

3. *Complete least cost pathways analysis for NWT conservation action EWRR assessment.*
   NU will combine data from Scotland into the modelling framework to assess the least cost pathways across the entire Kielder area. The data from the early warning system will be compared to the modelling output to assess the optimisation of the approach. A manuscript will be prepared for publication.

APPENDIX: SOFTWARE AND METADATA REFERENCES

R packages and software references

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All ecological models are developed using the R environment. Specialised packages used in the modelling process include:

- 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, raster, geosphere, RColorBrewer
- for modelling: unmarked, pscl, lme4
- for data editing: stringr, zoo, lubridate, ggpubr, scales, chron, zoo

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Metadata

Robust models using high quality fine scale data are necessary to investigate the relationship between culling practices at these locations and grey squirrel abundance. The data simulation uses several scales of metadata accordingly with the processes driving red and grey squirrel abundance.

Metadata (Table 4) were retrieved initially for the sites local to partners and include 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) which can be incorporated into simulation framework to produce an array of scenario-dependent output.

Table 4: 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	Available online: http://www.metoffice.gov.uk/pub/data/weather/uk/cl	Provided as monthly and seasonal values. Also computed as

	Rain (mm) Number of air frost days Number of rain days (>1mm)	imate/datasets/Tmax/date/England_E_and_NE.txt	- 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