A Systematic Map of Research Exploring the Ecological Modifiers and Consequences of Bark Damaging Behaviour in Squirrel Species

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Abstract

Bark-stripping and browsing by mammals in woodlands can cause widespread damage to trees, inhibiting tree growth and leading to whole tree or canopy death. Sciurid species worldwide are known to incorporate inner bark or cambium tissue into their diets, and outer bark can additionally be used as nesting material. The drivers and causes of bark-stripping behaviour have been investigated and determined for some species; for others this remains largely unexplained, including the eastern grey squirrel *Sciurus carolinensis*. For all squirrel species there is good understanding of tree susceptibility to damage as well as impacts of damage on tree health. However, much less is known about the drivers and modifiers of bark-stripping behaviour, which hinders the development of effective mitigation and management efforts. To address this knowledge gap, we aim to produce a systematic map, by collating, organising and categorising knowledge clusters and gaps on motivators of bark-stripping behaviour in squirrels, and the consequences of bark damage by squirrels in woodlands globally. Literature searches will be conducted in English, Spanish, Simplified Chinese, and Traditional Chinese using relevant scientific databases (ISI Web of Science, Scopus, SciELO, Wanfang, NDLTD and NCLTPL). The relevant search terms are defined by a primary question: what are the correlates and consequences of bark-damaging behaviour caused by squirrel species in woodlands, and what are the recommended management strategies? Papers will be screened for inclusion criteria at two stages: (1) abstracts and titles, and (2) full-texts. Information extracted from the studies will include study location, publication date, publication type, length of study, regional scope of study, data type, sampling strategy, study design, and intervention methods. Further coding variables will be used to extract relevant data, recording the modifiers and consequences of bark-stripping behaviour at different spatial scales. Results will be presented visually and narratively, summarising key characteristics of the systematic map database and identifying areas for new evidence syntheses and primary research.

Background

Invasive species from the tree squirrel family Sciuridae have propagated throughout the globe, with many causing extensive ecological and economic damage. The most notable of these may be the invasive eastern grey squirrel *Sciurus carolinensis* introduced to various locations outside of its native distribution of eastern North America. The eastern grey squirrel was introduced to Britain and South Africa in the late 1800s as well as Australia, Italy, Mexico, Canada, and western North America in the 1900s (Palmer *et al.* 2007). The eastern grey squirrel not only extirpated the native red squirrel *Sciurus vulgaris* from much of mainland Britain, but has additionally caused widespread economic damage to trees via bark-stripping behaviour (Kenward *et al.* 1988a; Wauters, Tosi and Gurnell, 2002). Other invasive sciurid species are also known to bark-strip, such as the red-bellied squirrel *Callosciurus erythraeus* and Finlayson's squirrel *Callosciurus finlaysonii* introduced to Italy, Argentina, and Japan in the mid to late 20th century causing extensive tree damage in these countries (Bertolino *et al.* 2004; Tamura and Ohara, 2005; Pedreira *et al.* 2020). Moreover, many other tree squirrel species within their native ranges also cause damage, such as the North American red squirrel *Tamiasciurus hudsonicus* in Canada (Brockley and Elmes, 1987), the Eurasian red squirrel *Sciurus vulgaris* in Britain and mainland Europe (Kenward, 1983), the red-bellied squirrel in Taiwan (Kuo and Ku, 1987), and the tassel-eared squirrel *Sciurus aberti* in North America (Allred, Gaud and States, 1994). The motivations for bark-stripping behaviour are understood in some species, whilst remaining speculative in others. The Abert's squirrel of North America is driven by winter food shortages to feed on the inner bark of twigs of ponderosa pine *Pinus ponderosa* (Allred, Gaud and States, 1994). Other species such as the eastern grey squirrel bark-strips in spring and early summer when other foods are readily available. This suggests that their behaviour may have little relation to food availability, however nutrients in bark may be required for growth in juveniles, and gestation or lactation in females (Kenward, 1983).

Much research has been dedicated to determining tree susceptibility to bark damage by squirrels and many other small mammals. Whilst the consequences of bark-stripping on tree health are well studied, the impacts of bark-stripping on other ecosystem services beyond timber are not well understood. Additionally, patterns of bark-stripping vary at different temporal and spatial scales making the behaviour appear sporadic (Kenward *et al.* 1988b). Awareness of how drivers for bark-stripping behaviour operate at different spatial scales could provide new information on casual mechanisms for bark-stripping. The lack of causal understanding hinders the development of effective management strategies for many species that bark-strip. With a better awareness of the motivations and drivers for bark-stripping behaviour, management and control methods could be adequately tailored to the behaviour, yielding more fruitful outcomes (Kenward, 1981). Bark stripping by the eastern grey squirrel is extensive across Britain, and the Royal Forestry Society states that this type of damage is the "number one threat" to British broadleaf woodlands, following their 2021 survey (Necar, 2021). Current recommended methods of control include lethal trapping and shooting (Lawton, 2003; Gill *et al.* 2019); however, these methods are often only effective for a limited amount of time, are labour and economically intensive, and are only successful at large spatial scales (Mill *et al.* 2020).

Squirrels are rarely observed in the act of bark stripping, which hampers acquisition of knowledge on the underlying causal mechanisms of this behaviour. However, observations of previously damaged stands are relatively easily undertaken and provide evidence on the susceptibility of tree species and age classes, which is useful information for forest management and potentially also provides clues to mechanisms. The arboreal ecology of tree squirrels makes them difficult species to study (Moore *et al.* 2021). Overcoming this barrier will help to improve the understanding of this behaviour. Currently, no syntheses have attempted to comprehensively review all the literature pertaining to bark-stripping in squirrels across the globe. We aim to produce the first such synthesis, in the form of a systematic map of the bark-stripping literature of sciurid species, to provide a much needed research direction for investigating causal mechanisms of the behaviour. In the following protocol, we detail our methods for systematically mapping the wide range of possible drivers of bark-stripping behaviours in sciurids, and the evidence of interactions across spatial scales amongst factors relating to bark-stripping behaviour. This systematic map will help identify the major knowledge gaps and clusters that merit further syntheses and primary research.

Objective of the systematic map

The primary objective of this systematic map is to collate, organise and categorise the knowledge clusters and gaps within research that targets squirrel bark damage and its consequences for woodland health and growth.

Primary question

What are the correlates and consequences of bark damaging behaviour caused by squirrel species in woodlands, and what are the recommended management strategies?

Components of the primary question

Population: including studies of woodlands or forests where outer and/or inner bark has been damaged or consumed by a squirrel species.

Intervention: including studies that investigate the management of bark damage by squirrels in the form of shooting, bait-trapping, poisoning, silvicultural practices, provisioning of supplementary food etc.

Outcomes: including the identification of modifiers, consequences, and recommended management options. We are particularly interested in outcomes that identify interactions between different modifiers of squirrel bark damage, especially at different spatial scales.

Systematic map protocol

Literature sources

The review will adhere to standard methods of systematic mapping in environmental sciences, as described by guidelines from the Collaboration for Environmental Evidence (CEE, 2018). We will complete a Reporting standards for Systematic Evidence Synthesis (ROSES) checklist in accordance with Haddaway *et al*. (2018). The academic literature search will be conducted within ISI Web of Science (WoS) and Scopus for English literature; in SciELO for Spanish literature; and in Wanfang and the National Central Library of Taiwan Periodical Literature (NCLTPL) for Chinese literature in mainland China and Taiwan respectively. Since some relevant grey literature is unavailable within these databases, it will be sought by screening all literature at the Alice Holt Research Station, Forest Research UK. For searching Taiwanese grey literature, the National Digital Library of Theses and Dissertations in Taiwan (NDLTD) will be used. In addition, ‘Snowballing’ of papers will be performed on references cited in included studies (Wohlin, 2014), ensuring that they are subjected to the same inclusion criteria. Further, a comprehensive grey literature search following methods by Haddaway and Bayliss (2015) will be conducted, which includes all types of unpublished literature, such as student research and industry research. Two types of grey-literature search methods will be used: (i) a 'file-drawer' search in the form of author contacts and references to unpublished research within citations; and (ii) a 'practitioner-generated data' search to identify research outside of academia, which involves using industry contacts and non-governmental organisation (NGO) website searches, and reaching out to research producers via personal contacts, email lists and social networks.

The following specialist websites, particularly those run by NGOs, listed below will be searched for links, references and publications relevant to squirrel bark damage:

- UK Squirrel Accord: https://squirrelaccord.uk/
- The Mammal Society: https://www.mammal.org.uk/
- European Squirrel Initiative: https://www.europeansquirrelinitiative.org
- Forest Research: https://www.forestresearch.gov.uk/
- US Forest Service Research & Development: https://www.fs.fed.us/research/
- British Red Squirrel: https://www.britishredsquirrel.org/
- The Woodland Trust: https://www.woodlandtrust.org.uk/
- Institute of Chartered Foresters: https://www.charteredforesters.org/
- Vincent Wildlife Trust: https://www.vwt.org.uk/
- Gloucestershire Wildlife Trust: https://www.gloucestershirewildlifetrust.co.uk/
- European Mammal Foundation: https://www.european-mammals.org/
- Game & Wildlife Conservation Trust: https://www.gwct.org.uk/
- European Forest Institute: https://efi.int/
- Forestry knowledge Service System (China): https://forest.ckcest.cn/
- Taiwan Forestry Bureau: https://www.forest.gov.tw/EN/

Search terms in English
The literature uses various terms to describe bark and tree components, and bark-stripping and other debarking behaviours (Table 1). The literature search will therefore include multiple terms to link bark, damage, and squirrels. Advanced searches in the online literature databases WoS and Scopus will use the following search strings of English terms:

WoS: TS=((tree* OR bark* OR stem* OR wood* OR forest* OR bole* OR trunk* OR plantation* OR stand*) AND (damag* OR strip* OR ring* OR girdl* OR chew* OR forag* OR gnaw* OR peel* OR remov* OR diet* OR feed*) AND (squirrel* OR *sciur* OR funambulus*))

Scopus: (TITLE-ABS-KEY((tree* OR bark* OR stem* OR wood* OR forest* OR bole* OR trunk* OR plantation* OR stand*) AND (damag* OR strip* OR ring* OR girdl* OR chew* OR forag* OR gnaw* OR peel* OR remov* OR diet* OR feed*) AND (squirrel* OR *sciur* OR funambulus*))) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "VETE") OR LIMIT-TO (SUBJAREA, "EART") OR LIMIT-TO (SUBJAREA, "Undefined"))

The WoS search included all databases within WoS, without restriction to any specific research categories or subject areas (which otherwise omitted relevant papers).

Search terms in Spanish
An advanced search in the online literature database SciELO will use the following search string of Spanish terms:

((arbo* OR corteza* OR tallo* OR madera* OR bosque* OR selva* OR forestal* OR cultiv* OR fust* OR tronco*) AND (dañ* OR remo* OR descorteza* OR anil* OR descope*) AND (ardilla* OR sciur* OR tamiasciurus OR callosciurus OR funambulus) AND (dieta OR aliment*))

Search terms in Chinese
In the online literature database Wanfang, an advanced search of Chinese publications in the subset of journal articles, dissertations and theses, and conference papers will use the following search string of Simplified Chinese terms:

题名或关键词:((“松鼠” OR sciur OR funambulus) and (树 OR 木 OR 林 OR 森 OR 树干 OR 植 OR 茎 OR 梗 OR 种 OR 株) AND (撕 OR 剥 OR 害 OR 环 OR 嚼 OR 喂 OR 伤 OR 食 OR 养 OR 喂 OR 饲)) and 主题:(NOT 考 NOT 商 NOT 教育 NOT 学生 NOT 作文 NOT 化石 NOT 公司 NOT 企业)) and Date:1900-*

For Taiwanese publications, an advanced search of dissertations and theses in the NDLTD, and journal papers in the NCLTPL will use the following string of Traditional Chinese search terms:

NDLTD: ("松鼠".ab and ("樹" or "莖" or "木" or "林" or "森" or "幹" or "植" or "梗" or "種" or "株").ab) and ("傷" or "害" or "撕" or "扯" or "剝" or "環" or "嚼" or "啃" or "帶" or "喂" or "食" or "養" or "飼" or "吃").ab not "商務".ti /lg="中文"

NCLTPL: ALL= 松鼠 AND (害 OR "樹" OR "林" OR "害" OR "撕" OR "扯"OR "剝" OR "環" OR "帶" OR "嚼" OR"啃" OR "喂" OR "食" OR "養" OR "飼" OR "吃")

Table 1. Translation of search terms. Translation was not possible for all terms, terms used reflected the terminology used in English, Spanish, Chinese and Taiwanese literature.

	English search term	Spanish search term(s)	Simplified Chinese search term(s)	Traditional Chinese search term(s)
Terms describing tree/bark	Tree*	Arbo*	树	樹
	Bark*	Corteza*	树皮	樹皮
	Stem*	Tallo*	茎 梗	莖 梗
	Wood*	Madera*	木	木
	Forest*	Bosque* Selva* Forestal*	林 森	林 森
	Bole	Fust*	树身	樹身
	Trunk*	Tronco*	树干	樹幹
	Plantation*	Cultiv*	种 植	種 植

	Stand	Rodal*	株	株
Terms describing damage/feeding	Damag*	Dañ*	伤 害	傷 害
	Strip*	Descorteza*	撕 扯	撕 扯
	Ring*	Anill*	环	環
	Girdl*	N/A	带	帶
	Chew*	N/A	嚼	嚼
	Forag*	N/A	觅 食	覓 食
	Gnaw*	N/A	啃	啃
	Peel*	N/A	剥	剝
	Remov*	Remo*	去	去
	N/A	Descope*	N/A	N/A
	Diet*	Diet*	食 吃	食 吃
	Feed*	Aliment*	喂 饲 养	喂 飼 養
Terms describing squirrel	Squirrel*	Ardilla	松鼠	松鼠
	Sciur	Sciur*	Sciur*	Sciur*
		Tamiasciurus	N/A	N/A
		Callosciurus	Callosciurus	Callosciurus
	Funambulus	N/A	Funambulus	N/A

Comprehensiveness of Search

The CEE (2018) guidelines recommend testing the comprehensiveness of the literature search. Therefore, we identified a set of English and Spanish articles that we deemed essential to a comprehensive review of literature on the focal question (Table 2). Their capture by the systematic search and/or snowballing will corroborate comprehensiveness. Additionally, Pao-Chang (1988) outlines literature on red-bellied squirrel damage in Taiwan, which will aid in the assessment of comprehensiveness of the Taiwanese literature search.

Table 2. A list of English and Spanish studies used to assess the comprehensiveness of our search.

Full reference	**Study language**	**Focal squirrel species**	**Modifiers investigated**
Kenward, R.E. (1982). Bark-stripping by grey squirrels—Some recent research. *Quarterly Journal of Forestry*, *76*(2), pp.108-121.	English	*Sciurus carolinensis*	Behaviour and food availability
Brockley, R.P. and Elmes, E. (1987). Barking damage by red squirrels in juvenile-spaced lodgepole pine stands in south-central British Columbia. *The Forestry Chronicle*, *63*(1), pp.28-31.	English	*Tamiasciurus hudsonicus*	Relative tree growth and woodland type
Kenward, R.E., Parish, T., Holm, J., and Harris, E.H.M. (1988). Grey squirrel bark-stripping. I. The roles of tree quality, squirrel learning and food abundance. *Quarterly Journal of Forestry*, *52*(1), pp.9-20.	English	*Sciurus carolinensis*	Tree quality, squirrel behaviour and nutrition

Kenward, R.E., Parish, T. and Doyle, F.I.B. (1988). Grey squirrel bark-stripping. II. Management of woodland habitats. *Quarterly Journal of Forestry*, *82*(2), pp.87-94.	English	*Sciurus carolinensis*	Woodland management practices
Sullivan, T.P. and Klenner, W. (1993). Influence of diversionary food on red squirrel populations and damage to crop trees in young lodgepole pine forest. *Ecological Applications, 3*(4), pp.708-718.	English	*Tamiasciurus hudsonicus*	Reducing damage through food provision
Peterken, G.F. and Mountford, E.P. (1996). Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. *Forestry: An International Journal of Forest Research*, *69*(2), pp.125-136.	English	*Sciurus carolinensis*	Silvicultural thinning and drought
Sullivan, T.P., Klenner, W. and Diggle, P.K. (1996). Response of red squirrels and feeding damage to variable stand density in young lodgepole pine forest. *Ecological Applications*, *6*(4), pp.1124-1134.	English	*Tamiasciurus hudsonicus*	Stand density and relative tree growth
Mountford, E.P. (1997). A decade of grey squirrel bark-stripping damage to beech in Lady Park Wood, UK. *Forestry: An International Journal of Forest Research*, *70*(1), pp.17-29.	English	*Sciurus carolinensis*	Relative tree growth and apical dominance
Mountford, E.P. and Peterken, G.F. (2003). Long-term change and implications for the management of wood-pastures: experience over 40 years from Denny Wood, New Forest. *Forestry*, *76*(1), pp.19-43.	English	*Sciurus carolinensis*	Tree species
Rayden,T.J. and Savill, P.S. (2004). Damage to beech woodlands in the Chilterns by the grey squirrel. *Forestry*, *77*(3), pp.249-253.	English	*Sciurus carolinensis*	Tree age and species diversity
Tamura, N. and Ohara, S. (2005). Chemical components of hardwood barks stripped by the alien squirrel *Callosciurus erythraeus* in Japan. *Journal of Forest Research*, *10*(6), pp.429-433.	English	*Callosciurus erythraeus*	Tree chemical components
Mountford, E.P. (2006). Long-term patterns and impacts of grey squirrel debarking in Lady Park Wood young-growth stands (UK). *Forest ecology and management*, *232*(1-3), pp.100-113.	English	*Sciurus carolinensis*	Tree species diversity and relative growth
Signorile, A.L. and Evans, J. (2007). Damage caused by the American grey squirrel (*Sciurus carolinensis*) to agricultural crops, poplar plantations and semi-natural woodland in	English	*Sciurus carolinensis*	Tree species and surrounding habitat

Piedmont, Italy. *Forestry*, *80*(1), pp.89-98.			
Mayle, B.A., Proudfoot, J. and Poole, J. (2008). Influence of tree size and dominance on incidence of bark stripping by grey squirrels to oak and impact on tree growth. *Forestry*, *82*(4), pp.431-444.	English	*Sciurus carolinensis*	Tree size and dominance
Mori, E., Mazzoglio, P.J., Rima, P.C., Aloise, G. and Bertolino, S. (2016). Bark-stripping damage by *Callosciurus finlaysonii* introduced to Italy. *Mammalia*, *80*(5), pp.507-514.	English	*Callosciurus finlaysonii*	Tree species
Nichols, C.P., Gregory, N.G., Goode, N., Gill, R.M.A. and Drewe, J.A. (2018). Regulation of bone mineral density in the grey squirrel, *Sciurus carolinensis*: Bioavailability of calcium oxalate, and implications for bark stripping. *Journal of animal physiology and animal nutrition*, *102*(1), pp.330-336.	English	*Sciurus carolinensis*	Seasonal calcium deficiency
Pedreira, P.A., Penon, E.A. and Borgnia, M. (2020) Debarking damage by alien Pallas's squirrel, *Callosciurus erythraeus*, in Argentina and its effects on tree growth. *Southern Forests: a Journal of Forest Science, 82*(2), pp.118-124.	English	*Callosciurus erythraeus*	Consequence for tree growth and wood quality
Hilje, L. (1992). Daño y combate de los roedores plaga en Costa Rica. *Manejo Integrado de Plagas y Agroecología Número 23* (Marzo 1992), páginas 32-38.	Spanish	*Sciurus granatensis, Sciurus variegatoides*	Tree species
Bautista, E.V., Martínez, J.F.R., Cruz, L.S., Coronel, L.P.O., Sánchez, F.M., Garduño, M.V.G. and Sánchez, O.C. (2002). Diagnóstico sanitario de los bosques del Distrito Federal, México. *Revista Mexicana de Ciencias Forestales, 21*(91), pp.7-26.	Spanish (abstract in English)	*Sciurus sp.*	Tree species
Mora–Ascencio, P., Mendoza–Durán, Á. and Chávez, C. (2010). Densidad poblacional y daños ocasionados por la ardilla *Sciurus aureogaster*: implicaciones para la conservación de los viveros de Coyoacán, México. *Revista Mexicana de Mastozoología (Nueva Época)*, *14*(1), pp.7-22.	Spanish (abstract in English)	*Sciurus aureogaster*	Tree species
Flores, H.J.M., Zaragoza, O.H., Zaragoza, P.H., Magaña, J.J.G. and Ramírez, R.B. (2015). Comparación del crecimiento *Pinus chiapensis* (Martínez) Andresen, *Pinus greggii* Engelm. Y *Pinus patula* Schl. Et Cham.	Spanish	*Sciurus sp.*	Tree species

En Plantaciones Comerciales e Stablecidas en Hueyapan, Puebla. *Foresta Veracruzana*, *17*(1), pp.1-8.			
Lizarralde, M. (2016). Especies exóticas invasoras (EEI) en Argentina: categorización de mamíferos invasores y alternativas de manejo. *Mastozoología neotropical*, *23*(2), pp.267-277.	Spanish	*Sciurus sp.*	
Pedreira, P.A., Penon, E. and Borgnia, M. (2017). Descortezado en forestales producido por la ardilla introducida *Callosciurus erythraeus* (Sciuridae) en Argentina. *Bosque (Valdivia), 38*(2), pp.415-420.	Spanish (abstract in English)	*Callaosciurus erythraeus*	Tree species and DBH
Pedreira, P.A., Penon, E., Aguirre, E. and Borgnia, M. (2017). Impacto sobre el volumen de la madera en *Pinus elliottii* y *Eucalyptus dunnii* ocasionado por la ardilla de vientre rojo en un establecimiento productivo dentro del partido de Luján (Buenos Aires, Argentina). *Jornadas Forestales de Entre Rios, 31.*	Spanish	*Callaosciurus erythraeus*	Tree species and tree age

Screening and filtering of papers

Retrieved publications will be exported from the literature databases and other sources for import into the R environment (version 4.1.1.;R core team, 2021). The R package 'metagear' (Lajeunesse, 2016) will be used to screen titles and abstracts of included publications for their potential relevance to this review, based on the following criteria:

a. Include literature relating to bark damage by squirrels in woodlands. Exclude any damage by any other rodents, lagomorphs, and larger mammals such as deer and boar.
b. Include only literature written in English, Spanish, Simplified Chinese, and Traditional Chinese. Keep a record of all publications that are excluded on the basis of language. We recognise the limitations of not including literature in other non-English languages (Amano *et al.* 2016), namely Japanese literature that investigates damage caused by introduced the red-bellied squirrel. However, we do not have the resources to expand searches to include Japanese literature.
c. Include literature from journals regardless of whether or not they use peer-review, and include all relevant instances of unpublished and grey literature.
d. Include all study types (mensurative, experimental, conceptual, theoretical, modelling, etc).
e. Include all relevant literature regardless of date, within the scope of the databases and sources explored in the review (From 1950 for WoS, 1970 for Scopus,1920 for SciELO, 1950 for Wangfang, 1958 for NDLTD, and 1960 for NCLTPL). Snowballing will attempt to account for limitations due to date restrictions within literature database searches.

Coding variables and production of a systematic-map database
Meta-data will be extracted from all included papers in the form of coding variables, which categorise key elements of each paper for the purpose of organising relevant information. Table 3 describes the full list of these variables.

Table 3. Meta-data coding variables and description.

Coding variable	Description
Full reference	Author, title, date, publisher
Date of publication	Year of publication
Publication type	Academic journal, book, conference paper or thesis
Country of study	Name of country / location
Length/ period of study	Time period (months)
Regional scope of study	Area of study: a woodland, forest, county, region etc.
Data type	Quantitative or qualitative
Sampling strategy	Randomised, systematic etc.
Study design	Experimental, observational, survey, review etc.
Intervention methods	Woodland management strategies including thinning practices and culling via shooting, bait trapping, poison etc.
Perspective	Was the study designed from the perspective of trees, investigating tree susceptibility and severity of damage; or from the perspective of squirrels, investigating the drivers of bark-stripping behaviour.

We used the hierarchical selection orders proposed by Johnson (1980), in order to develop further coding variables that reflect the hierarchical nature of ecological modifiers at the regional-, landscape-, local-, and individual-scales in relation to bark damage by squirrel species. An abundance of data and evidence exists to support different theories of bark damaging behaviour, and drivers for the behaviour can vary greatly within and between species. For some species, the exact mechanisms for inducing bark damaging behaviours are unknown and remain speculative (Kenward, 1983; Nichols *et al.* 2016), and some studies cite multiple different factors and their interactions as drivers of the behaviour (Spake *et al.* 2020). Additionally, we will use a coding variable to identify whether proposed modifiers were built into the design of the study, or discussed post-hoc. Table 4 defines the coding variables for each of these modifiers.

Table 4. Definitions of coding variables for modifiers explaining bark damage by squirrels at different spatial scales.

Coding variable	Category	Definition
Regional-level modifiers	Drought	A record of drought during or just preceding a bark damaging event (yes/no).
	Precipitation	A measure of precipitation before and during damage (mm).
	Temperature	A measure of temperature before and during damage (°C)

	Conspecifics	Density of squirrels within the damaged area (squirrels/ha).
	Seed/Nut Masting	A record of a mast year preceding a bark damaging event (yes/no).
Landscape-level modifiers	Woodland cover	The amount of woodland cover within the surrounding landscape (ha).
	Open landscape cover	The amount and extent of open land-cover such as arable and grassland within the surrounding landscape (ha).
	Residential areas	Proximity of damaged woodland to built-up areas, with high road and human density (m).
	Culling / pest control	The presence of control methods to regulate population density of squirrels within the damaged woodland (present/absent).
	Control method	The control method used to manage damage, whether it was recommended or executed, and whether it was successful or unsuccessful in execution.
Local-level modifiers	Woodland type	Woodland type of damaged woodland (i.e.: deciduous, mixed, or coniferous).
	Tree density	A measure of tree density within the damaged woodland (stems/ha).
	Tree age diversity	Tree age classification within the damaged or investigated woodlands (i.e.: young growth, old growth, uneven aged).
	Silvicultural practices	The silvicultural system implemented within the damaged woodlands.
	Forest size	The total forest area where bark damage occurred (ha).
	Tree species diversity and composition	An index of tree species diversity and composition within the damaged woodland and adjacent woodland.
	Average DBH	Average diameter at breast height (DBH) of all trees in the woodland studied.
	Soil type and quality	The soil type and quality present.
	Visitor pressure	Presence or absence of public access to the woodland site.
	Woodland condition	Any measure of overall woodland condition.
Individual-level modifiers (squirrel)	Species	Species of squirrel that caused any amount of bark damage.
	Sex	Sex of squirrels causing the damage.
	Age	Average age of squirrels causing the damage.
	Diet	Damaged modified by the nutritional requirements of a squirrel species (yes/no).

	Health	Health impediments of squirrels performing any bark-stripping behaviour (i.e., disease, deficiency).
	Breeding condition	Bark damage carried out by a pregnant, lactating, post-lactating female, or non-breeding male or female.
	Behaviour	Bark damage derived from antagonistic, territorial, or learned behaviour.
	Breeding season	Bark damage occurring during the primary breeding season of a species (yes/no).
Individual-level modifiers (tree)	Species	Species of tree damaged.
	Tree origin	Native, non-native, naturalised or invasive.
	Species not damaged	Any species of tree present in the damaged area, but has not experienced damage.
	Age	Average age of trees damaged.
	Age not damaged	The range of ages of trees left undamaged.
	Nutritional value	A nutritional component identified within the tree phloem or bark consumed (i.e.: calcium, carbohydrates, phosphorous, sodium).
	Previous damage	If trees damaged have been damaged previously, indicating recurring damage events (yes/no).
	Health	Condition of trees compromised by disease or other damage (i.e.: fungus, infection)
	DBH	Average diameter at breast height (DBH) of trees damaged relative to undamaged neighbouring trees, used as a proxy for relative growth.

The consequences and effects of bark damaging behaviour can operate at different ecological scales. A set of coding variables were therefore developed for factors that explain consequences of squirrel bark damage at different spatial scales and/or in interactions with each other (Table 5).

Table 5. Definitions of coded variables for factors describing the consequences of bark damage by squirrels operating at different spatial scales.

Coding variable	Category	Definition
Landscape-level effects	Woodland cover	Area of tree cover reduced as a result of bark damage.
	Carbon sequestration	The ability of a forest to sequester carbon has been diminished due to bark damage (yes/no).

Local-level effects	Tree diversity and composition	Bark damage has altered the diversity and composition of trees within a woodland (yes/no).
	Tree density	Damage has altered the density of trees within a woodland (yes/no).
	Woodland Management	Woodland owners have altered their management and silvicultural systems to adapt to bark damage by squirrel species (yes/no).
Individual-level effects (tree)	Disease/Injury	Disease or physical injury has resulted from bark damage (yes/no).
	Structural damage	Type of structural damage to the tree such as wind-snap as a result of damage.
	Reduced growth rate	Bark damage has affected tree growth (yes/no).
	Loss of dominance	Apical dominance of a tree has been lost due to bark damage (yes/no).
	Death	Bark damage resulted in the death of the tree (yes/no).
	Level of damage	Percentage of trees damaged by squirrels.
	Loss of timber quality	Bark damage has diminished the timber quality of a tree, rendering it unsellable(yes/no).

Critical appraisal

Whilst reviewing the articles contributing to this literature review, a parallel critical appraisal will be applied to all open-access articles and those granting full-access to the University of Southampton. The University of Southampton provides access to a variety of academic journals, with the library system currently holding 190,243 electronic journal titles. The CEE Critical Appraisal Tool version 0.3 (Konno *et al.* 2021) will be used to code for risk of bias in interpretation or of speculation in explanation. Each included study will be scored as having low, medium or high risk of bias or speculation, based on a lack of evidence base or dependence on untested assumptions. Although this is an optional step within systematic map methodologies (James, Randall, and Haddaway, 2016), it is particularly important here given the many competing theories for the causes of eastern grey squirrel damage in the UK. Critically appraising the current literature aids in identifying those hypotheses and theories of bark damage by squirrels that are supported with sufficient evidence and sound methodology. This additional step will aid in the production of an accurate map of our current knowledge pertaining to bark-stripping behaviours, and will inform where to focus future research efforts.

Visualising the systematic map

Information extracted from each paper will be collated into a database within the R environment. The R packages ‘ggplot’, ‘tdyr’, and ‘dplyr’ will be used to help organise and visualise the data. Metadata will also be presented as a layer in a Geographical Information System (GIS) depicting the location of squirrel damage reported in studies across the globe, and regional variation in modifiers of damage.

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