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Resilience and tree health: a basis for implementation in sustainable forest management

Lauren Fuller[1,3]* and Christopher P. Quine[2]

[1]*Forest Research, Centre for Ecosystems, Society and Biosecurity, Alice Holt Lodge, Farnham GU10 4LH, UK*
[2]*Forest Research, Centre for Ecosystems, Society and Biosecurity, Northern Research Station, Roslin, Midlothian EH25 9SY, UK*
[3]*Present address: University of Stirling, Stirling FK9 4LA, UK*

*Corresponding author. E-mail: laurenvfuller@gmail.com

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Resilience is rapidly becoming a prominent concept in research, policy and practice. However, it is apparent that there is no consistent meaning of resilience being used by those involved in governing and managing forests and tree health. We aimed to (1) identify how the concept of resilience is defined in a range of decision-making contexts, (2) develop an understanding of resilience, which will be useful in the context of tree health and forestry and (3) suggest how managers could use this understanding more broadly as a framework for decision-making on resilience within the forestry sector. Implementation of resilience for tree health needs to encompass a range of functions and services, management objectives and threats, all present at a variety of scales. We conclude that, due to the complexity of the resilience concept and forest systems, no single definition of resilience can be sufficient and it is more appropriate to explicitly consider four resilience components: resistance, recovery, transformation and adaptation. We propose a set of decision steps which stakeholders can use to develop a Resilience Implementation Framework to guide management for their system of interest.

Introduction

The concept of resilience is gaining prominence in research, policy and practice across many disciplines and across applications to society, economy and the environment (Almedom, 2009; Allen *et al*., 2011; Defra, 2011; UK Government, 2013; Spears *et al.*, 2015). Interest in the concept in the forestry sector is partly a result of the increase in known and unknown threats to trees and forests, through processes such as climate change and increased global trade networks introducing new pests and diseases (Millar *et al*., 2007; Read *et al*., 2009; Gilligan *et al*., 2013). There are potentially many unidentified threats to tree health, and unexpected consequences such as larch death from *Phytophthora ramorum* in the UK illustrate the high level of uncertainty when dealing with tree health (Brasier and Webber, 2010). This uncertainty over unknown threats, unexpected effects and the potential magnitude of known threats such as climate change is a key driver for incorporating resilience into forest planning.

The impact of disturbances such as pests and diseases on trees and forests has cascading effects on ecosystem services, such as carbon storage, flood management, wildlife habitat, recreation and cultural values, and wood products (Boyd *et al*., 2013). The idea of increasing the resilience of trees and forests to a wide range of threats, and so protecting ecosystem services, is an attractive proposition for policy-makers and managers in the face of great uncertainty. However, if the concept of resilience is going to be successfully incorporated into policy and practice, it is essential that decision-makers understand the concept (Newton and Cantarello, 2015) and how it relates to different forest planning contexts within sustainable forest management (SFM).

In the UK, for example, the UK Forestry Standard provides a set of guidelines for forest managers and defines resilience as the 'ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change' (Forestry Commission, 2011). Defra's Tree Health Management Plan states that it aims to 'build the social, environmental and economic resilience of our tree population' (Defra, 2014) and defines resilience in the context of the environment as 'the capacity of the system to resist damage and recover quickly when challenged by environmental pressure'. There are also frequent references to resilience, but no specific definition, throughout the Forestry and Woodlands Policy Statement (Defra, 2013) not only in the context of woodland ecology but also of the entire forestry sector, which encompasses economic and social aspects. These documents illustrate how decision-makers are faced with diverse definitions and applications of resilience even within a particular sector.

More broadly, a variety of definitions of resilience in the literature, both within and between disciplines, in addition to attempts to widen the scope of resilience, have resulted in descriptions, which are increasingly vague and hard to operationalize (Brand and Jax, 2007; Newton and Cantarello, 2015). A key problem with defining resilience is that it is a social construct rather than a tangible and measurable process or phenomenon. Resilience implies a desirable state, but the specifics of what is desirable are based on social and normative judgements and values, which can vary widely between disciplines, organizations and individuals (Brand and Jax, 2007; Nelson *et al.*, 2007). There are numerous review papers that attempt to collate the definitions of resilience and focus the meaning of the concept (Luthar *et al.*, 2000; Walker *et al.*, 2006; Brand and Jax, 2007; Davydov *et al.*, 2010; Bhamra *et al.*, 2011). However, these tend to be unrelated to the issues faced in the forestry sector and are rather abstract and difficult to apply in real-life situations.

Different ideas about what constitutes resilience can have both positive and negative consequences. On one hand, differences in understanding can lead to shared learning between policy-makers and practitioners. However, there is also the risk that differences in understanding could lead to confusion about how policy or management for resilience should be directed. Evidently, there is a need to develop a clearer and more comprehensive understanding of the concept.

In response to this, we aimed to (1) identify examples of how the concept of resilience is defined and used in a range of decision-making contexts, (2) develop an understanding of resilience which will be useful in a tree health context and (3) suggest how managers could use this understanding more broadly as a framework for decision-making on resilience for the forestry sector.

Method

We carried out a literature review to identify how the concept of resilience is defined. Stakeholder consultations were used to validate our literature review findings and investigate how resilience is viewed in the context of tree health. This information was examined to develop a framework for decision-making. See Supplementary data for a full description of the literature review methodology, search results and stakeholder workshop consultations.

Literature review

The literature review incorporated several aspects of systematic review methodology to ensure a standardized and rigorous review process (Collaboration for Environmental Evidence, 2013; Woodcock *et al.*, 2014; Haddaway *et al.*, 2015). To achieve this, we used the following protocol: (1) scoped and defined search terms and Boolean operators, (2) documented the databases and organizations searched for published and grey literature, (3) defined inclusion criteria for relevant literature and (4) described the strategy for extracting information from the included studies.

Starting with a list of 10 relevant papers, we tested how many were returned by various combinations of search terms and Boolean operators. The intention was to capture most of the relevant articles whilst minimizing the number of non-relevant results; this ensured that the search terms used were targeted and comprehensive (Table 1). Specific inclusion criteria were used to assess the relevance of the articles returned in the search and determine inclusion or exclusion from the synthesis. The inclusion criteria were as follows: (1) must be written in English, (2) the source must be an article, editorial, report, review or abstract, (3) the title must contain the word resilience/resilient/resiliency, (4) the articles must have electronically available abstracts and texts and (5) the text must clearly state a definition of resilience (either new or pre-defined).

An Excel spreadsheet was used to record the following information about the articles chosen for inclusion in the synthesis: the date each article was reviewed; the type of literature (e.g. journal article, report); the subject area (e.g. environmental, social or economic); a short reference (author, date, title); whether the definition was original or repeated other literature; whether it was primary research or a review article; and whether the study informed decision-making and operationalization of resilience.

Stakeholder consultation

We consulted with policy-makers, practitioners and industry representatives involved in tree health and forestry at two stakeholder workshops. The first workshop involved 29 stakeholders, consisting of policy advisers, forest managers, practitioners and researchers. Round table discussions were used to explore stakeholder views on the definitions of resilience in the literature and to identify the strengths and weaknesses of the resilience concept in a tree health context. A second workshop sought to gain insights from 62 stakeholders involved in policy, natural resource management and natural resource-based trades. Round table discussions were used to explore stakeholder views about how system identity, scale and type of threat influenced their understanding of the resilience concept.

Framework development

We conducted a qualitative analysis of the data extracted from the literature review and validated this with evidence derived from the stakeholder consultations. From this analysis, we identified emerging key themes relating to defining and operationalizing the concept of resilience. These key themes were developed to form a framework for decision-making on resilience for tree health and the forestry sector.

Results

Definitions of resilience

Since system, structure, function and service are consistently referred to in the resilience literature, and subsequently in this review, we begin by defining these four terms. A system is a set of interacting components which form an integrated state and structure is the organization and relationships between the components of a system. Functions are the processes that occur within a system and services are the benefit gained from particular functions.

Table 1 Search terms and Boolean operators used in the literature search

		Resilience of...				Resilience to...
resilien*	AND	biodiversity OR diversity OR species OR ecological OR economy OR socio-economic OR timber OR wood* OR livelihood OR social OR recreation OR tourism OR market OR ecosystem OR cultur* OR forest* OR agricultur* OR infrastructure OR services OR function* OR environment* OR sustain* OR communit*	OR	resillien*	AND	pest OR pathogen OR disease OR climate OR pollution OR disturbance OR disaster OR invasive OR flood OR fire OR weather OR epidemic OR drought OR change

In the resilience literature, events that affect the ability of a system to persist in its current or desired state are referred to using a variety of different synonyms, such as disturbance, threat, catastrophe, crisis, damage, disaster, disruption, perturbation and shock; in common use, many of these words imply a negative outcome but we do not assume all consequences are such. In this review, we use both disturbance and threat to describe these events.

Of the 170 articles/reports reviewed, a few main authors were consistently cited. Where the definition was not attributed to one of these authors, it was generally a re-wording of previous work. The amount of repetition encountered indicates the current review is sufficient for capturing the different definitions; reviews generally reach information saturation, in which additional studies re-iterate existing viewpoints and do not increase understanding (Gough *et al*., 2013; Haddaway *et al*., 2015).

The literature search resulted in articles from a broad subject base, and these were subsequently divided into nine main subject areas. Key references were selected to represent the definitions of resilience commonly used in these subject areas (Table 2). Despite the range of subject areas reviewed, studies tended to directly cite definitions from other authors or adapt such definitions, with a predominance of those from the disciplines of engineering and ecology (e.g. Holling, 1973, 1996; Pimm, 1984; Ludwig *et al*., 1997; Walker *et al*., 2004). We therefore distinguish two broad definitions: 'engineering resilience' (the ability of the system to retain a steady state or the speed at which a system returns to a steady state following a disturbance (Pimm, 1984; Holling, 1996)) and 'ecological resilience' (the magnitude of disturbance that can be absorbed before the system transforms to another state (Holling, 1973)) (Table 2).

Engineering resilience is concerned with only one possible system state and the ability of the system to absorb disturbance and continue functioning in that state, known as resistance, or to experience disturbance but recover to the pre-disturbance state. Ecological resilience is concerned with the persistence of systems which typically operate far from a steady state and have multiple distinct states or states that range across a continuum of structure and function. The notion of various possible states is related to 'thresholds' or 'tipping points', where the magnitude of disturbance exceeds the capacity of the system to resist or recover, and the system fundamentally changes. Brook *et al*. (2013) defined tipping points as a small change in conditions which leads to a strong change in the state of a system.

The definition of ecological resilience has been further developed by researchers in the field of social-ecological systems, which is concerned with how society influences and values ecosystem functions

Table 2 Typical examples of resilience definitions from the main subject areas

Subject area	Definition	Authors
Computing	'the ability of a network to provide service despite external failures and the time to restore service when in the presence of such failures'	(Whitson and Ramirez-Marquez, 2009)
	'the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation'	(Sterbenz *et al*., 2010)
Engineering	'property that permits a stable system state to be maintained and/or recovered'	(Wreathall, 2006)
	'the ability to return to the steady-state following a perturbation'	(Hollnagel, 2014)
Mental health	'the positive capacity of people to cope with stress and adversity... bouncing back to a previous state of normal functioning, or ... produce a steeling effect and function better than expected'	(Masten, 2001)
	'resist the potential negative consequences of the risk and develop adequately'	(Engle *et al*., 1996)
Physical health	'achieve equilibrium or re-establish homeostasis following a provocation'	(Varadhan *et al*., 2008)
	'successful or positive recovery'	(Irwin, 2014)
Economic	'ability to maintain the flow of goods and services for which it is valued'	(Perrings, 1998)
	'The ability of a system to maintain function when shocked or the speed of recovery from a shock'	(Rose, 2004; Rose, 2007)
Planning	'existing abilities to resist, absorb, react, accommodate to, and recover'	(Borg *et al*., 2014)
	'able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life'	(Mileti, 1999)
Ecology	'capacity of an ecosystem to resist disturbance and still maintain a specified state'	(Grimm and Wissel, 1997)
	'the capability of an ecological system to absorb disturbance without collapsing and reorganizing into a different ecological state'	(Gunderson *et al*., 2010)
Social-ecological	'the amount of disturbance that a system can absorb before changing to another stable regime, which is controlled by a different set of variables and characterised by a different structure'	(Gunderson and Holling, 2002)
	'the magnitude of disturbance that can be absorbed before a system changes to a radically different state'	(Adger, 2006)
Business/organizational	'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed'	(Christopher and Peck, 2004)
	'an easy and rapid return to system functioning after disruption; this requires multi-equilibrium states to exist'	(Bhattacharya *et al*., 2013)

and services. The social-ecological use of resilience includes adaptation or undergoing transformation to another state as part of the resilience process (Folke, 2006). Social-ecological resilience also identifies two types of resilience: specific and general. Specific resilience, introduced by Carpenter *et al.* (2001), emphasizes the need to identify resilience 'of what, to what', essentially what system structure is of interest and to what threats it needs to be resilient. General resilience is concerned with a more broad-spectrum type of resilience where any or all components of a system have the capacity to be resilient to known and unknown threats (Folke *et al.*, 2010; Carpenter *et al.*, 2012).

Stakeholder consultation results

The broad stakeholder base resulted in a diverse range of interests and concerns about the resilience concept in relation to tree health and different ideas about the identity and spatial and temporal scale of the system of interest. The key findings from stakeholder discussions are represented in Table 3. Many stakeholders were interested in ecological resilience of woodlands and the ecosystem services they provide, although some thought of the forestry sector or their own business as a possible object for resilience. Threats were seen as largely pest and pathogen related and linked, for example, to consumer demand for exotic plants, although it was noted that other pressures (e.g. climate change, grazing and pollution) are likely to interact. In some cases, internal threats such as use of monocultures and loss of genetic diversity were also identified.

There was clear potential for confusion when the concept was applied uncritically to satisfy the demands of those working at different scales and with different ideas about which system functions are important. Different contexts and different threats will require different solutions, and there was a lack of clarity over who would be involved in decision-making (e.g. defining the boundaries of systems, deciding on the bounds of acceptable change, and choosing appropriate solutions and pathways to resilience). It was generally agreed that attempting to simplify the concept of resilience and the range of potential solutions might imply greater certainty about the appropriateness of particular pathways than is the case. Stakeholders also wished to avoid promoting acceptance of a single preferred state (e.g. preferred woodland species composition).

Decision-making framework

Resilience processes and examples

Descriptions of resilience consistently referred to four main components are as follows: resistance, recovery, transformation and adaptation. We suggest these four components offer scope for clear application of the resilience concept in forest systems, particularly when there is a combination of environmental, social and economic interests. The role these components play can be more simply demonstrated by describing three processes, which may occur when a system is faced with disturbance (illustrated in Figure 1): (1) 'Resistance' to disturbance by absorbing it and continuing to function in the same state; this is linked to the buffering capacity of the system; (2) 'Recovery' either to the pre-disturbance state or to an alternate system state that has essentially the same structure and function; this is achieved through 'adaptation'; (3) 'Transformation' to form a new state with different state variables when recovery or analogous alternate states are not possible; this is also achieved through 'adaptation'. Depending on the system and scale of interest, some or all processes may apply. Additionally, if the system is known to be moving towards a degraded state, it is possible to initiate a transformation before it no longer functions as required.

Resistance is the first line of defence against disturbance and focuses on before-crisis activities to increase the buffering capacity of the system (Lettieri *et al.*, 2009). For example, Dothistroma Needle Blight (DNB) is affecting *Pinus radiata* forests in New Zealand. Here, the foresters are unwilling to move away from growing this crop and as a result are using fungicide application, heavy thinning and breeding resistant strains to increase the resistance of *P. radiata* (Bulman *et al.*, 2004, .2008).

Many definitions of resilience include resistance either as a necessary component (Grimm and Wissel, 1997; Fiksel, 2003; Walker *et al.*, 2004; Martin, 2012) or a complementary attribute (Carpenter *et al.*, 2001). However, others view resilience as an after-crisis activity (Dearnley, 1976; Wildavsky, 1988; Lettieri *et al.*, 2009; Zhang and Lin, 2010) where a disturbance has exceeded the buffering capacity of a system and resistance has failed. The latter aligns more closely with DeRose and Long's (2014) conceptual framework where resistance is the effect of the structure and composition of a forest on disturbance and resilience is the effect of disturbance on subsequent forest structure and composition.

Recovery and transformation are important processes when resilience is seen as an after-crisis activity and are demonstrated as an adaptive process (Moench, 2009). Natural regeneration after fire, windthrow or pest and disease outbreaks provide good examples of recovery, often via adaptation and also highlight the long-time periods (e.g. centuries), which may be involved. Current policy in Britain advocates natural regeneration of semi-natural woodlands as the preferred means of recovery from pests and diseases, e.g. regeneration of ash trees affected by Chalara ash dieback

Table 3 Key findings from stakeholder workshop

Strengths of the resilience concept	Considerable interest as it currently has a strong resonance with policy and practice, both locally and nationally. A multi-faceted concept which embraces the dynamic nature of systems and incorporates a range of objectives, multiple threats and links socio-economic concerns with ecology. Encourages learning from past mistakes.
Weaknesses of the resilience concept	Lack of common understanding about the definition of resilience, with some stakeholders more focussed on resistance whereas others were concerned with adaptation to change or methods to achieve recovery. Operationalizing and measuring resilience is not easy and therefore success could not be monitored and demonstrated to stakeholder groups. Definitions of resilience are unclear, and it is not a meaningful concept without context.

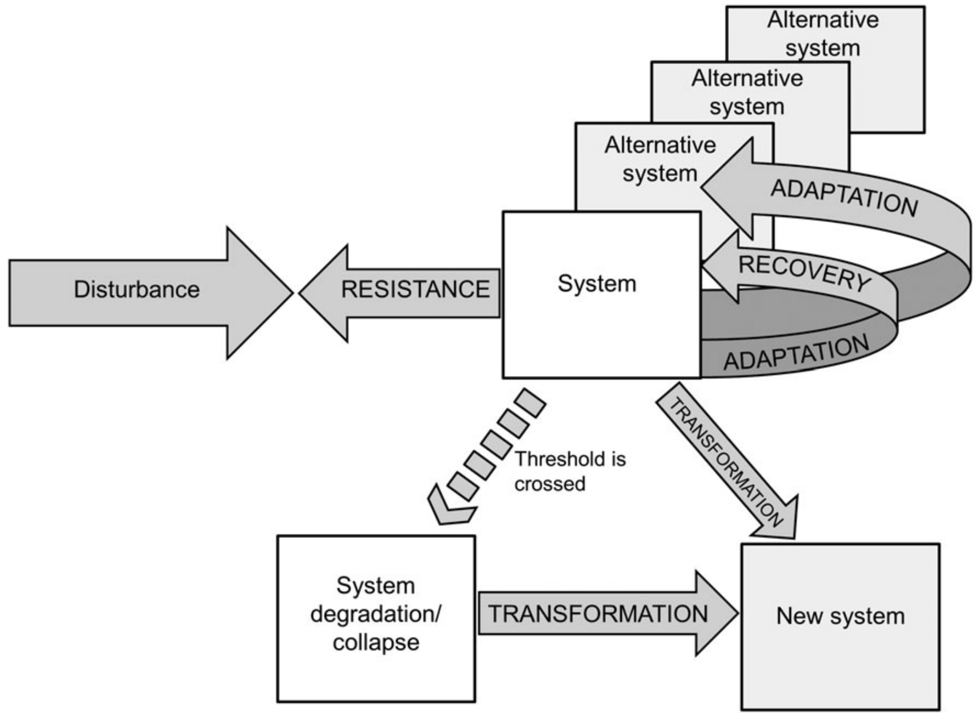

Figure 1 Diagrammatic representation of the concept of resilience; terms in capital letters indicate key components of resilience.

(*Hymenoscyphus fraxineus*) (Anon, 2003; Cavers and Cottrell, 2015).

If the pre-disturbance state cannot be recovered or the cost of recovery is too high then adaptation to the new state must occur. Alternatively, if the new state is not desirable then transformation becomes an important strategy (Carpenter *et al*., 2001; Nelson *et al*., 2007). In these circumstances, the system must be managed in a way that helps transform it to a desirable state (Walker *et al*., 2004; Anderies *et al*., 2006), although this may require a change in state variables and appropriate scales (Holling and Gunderson, 2002; Walker *et al*., 2004; Folke *et al*., 2010). For example, Thetford Forest in the east of England is mostly comprised of Corsican pine and is also suffering from an outbreak of DNB. As a result, diversification has become a priority and managers are trialling a number of different tree species to determine those which can be successfully grown, in order to continue providing the same goods and services (i.e. timber, recreation, wildlife habitat). In this way, they have utilized the opportunity to learn from experience and create a more diverse and hopefully more resilient forest. In contrast to the resistance focussed approach in New Zealand, this is a case of transformation and is an example of adaptive management and building adaptive capacity (Carpenter and Brock, 2008; Folke *et al*., 2002).

Resilience implementation framework

Six key themes emerged from the literature review and stakeholder consultation: (1) defining the identity of the system, (2) ascertaining threats to the system, (3) deciding on acceptable changes to the system's structure or function, (4) identifying the appropriate resilience component, (5) selecting appropriate management actions and pathways and (6) introducing monitoring and learning from experience. We propose to begin operationalizing resilience through the following six-step Resilience Implementation Framework based on these themes (Table 4).

Step 1: Define the focal system

(a) What is the system identity?

This is principally dependent on the components that constitute the system, the relationships between components, and the ability of both components and relationships to maintain themselves continuously through space and time (Cumming and Collier, 2005). It may be necessary to make the distinction between species and ecosystems; a particular tree species might be the focus or it could be services provided by a woodland ecosystem. In our case, some stakeholders considered a tree species (such as ash woodlands) and its related ecosystem services (such as biodiversity) to be the focus, whereas others were thinking of their business (such as a forest nursery or sawmill) as the object.

(b) What spatial and temporal scales encompass your system?

Understanding and interpreting processes of disturbance and resilience relies on a clear understanding of the spatial and temporal scales, which encompass the system and which may affect the influence of disturbance on the system. Forests are present in the landscape at a variety of spatial scales and defining resilience requires specifying whether the forest of interest is an individual stand, several stands or a forest area that spans a whole landscape (DeRose and Long, 2014). In terms of the forestry sector, the system identity might involve the ecological characteristics of a forest, the social functions or the economic aspects of a forest-dependent business. In terms of temporal scale, it is important

Table 4 Resilience implementation framework: the six steps are illustrated using three contrasting examples of the focal system

Step	Action	Questions	Example 1: ecological	Example 2 – Business	Example 3 – Uncertain future
Step 1	Define the focal system	(a) What is the system? E.g. ecosystem, organization, business	Ash woodland in Derbyshire	Tree nursery business	Productive conifer forest
		(b) What is the temporal scale being considered? E.g. years, decades, centuries	Long term – century	Years to decades	Approximately 50 years (average rotation length for stands in forest)
		(c) What is the spatial scale being considered? E.g. local, catchment, regional, national	Regional	Local	Forest design plan within a catchment
		(d) What is the (primary) objective of interest in the system? E.g. what functions are to be maintained?	Nature conservation including provision of habitat and micro habitats for wide range of species	Business sustainability	Maintenance of a productive and healthy forest Functions include – timber supply, recreation, protection of water courses/ water supply, wildlife habitat
Step 2	Identify the threats to the system of interest	(a) What are the possible disturbances? E.g. are these biotic/abiotic?	Ash dieback; emerald ash borer (EAB) (not yet present); wild and domestic herbivores	Pests and diseases affecting growing stock; impact of pest and disease policies on the market (e.g. ash planting moratorium will impact on a nursery with a large ash stock)	Known: Windthrow Current suite of pests and diseases Market downturn (e.g. glut due to national level windthrow) Known unknowns: Unspecified pest/disease that threatens main tree species Fire (started by human activities)
		(b) What is the likely frequency within the timescale of interest? E.g. Pulse or prolonged disturbances?	Prolonged chronic pressures	Unknown, but may increase and may include pulse disturbances associated with particular pest and disease outbreaks	Depends upon selection of key disturbance and time horizon, but potentially: Chronic and frequent – windthrow, current pests Episodic and extreme – major windthrow; market downturn Uncertain – New pest and disease; fire
		(c) Are there synergistic effects? E.g. secondary pests/ diseases, which increase the damage caused by the primary pathogen	Potentially , e.g. Weakened trees encouraging insect attack	Potentially –, e.g. Diseased trees leading to reputational damage, loss of orders, financial status, investor confidence	Potentially, e.g. Regional-scale windthrow and market downturnLocal windthrow and insect pests
		(d) What factors may influence the effect of disturbance on the function/system? E.g. co-occurring stressors such as grazing animals	Co-occurring stressors – climate change	Availability of alternative tree species	Depends upon selection of key disturbance and time horizon, but potentially: Management choices over age and species structure National and regional actions to strengthen biosecurity

Step 3	Identify boundaries of acceptable change	(a) Is it described by structural changes? E.g. mortality of components of ecosystem; loss of habitat	Possible changes that are not acceptable – loss of mature woodland Changes that are acceptable – surrogate ash species providing replacement tree cover	One-off loss of a proportion of growing stock may be acceptable whereas repeated loss or long-term moratorium of a particular species may not be acceptable	Loss of mature component of forest – leading to change in visual aesthetics and habitat value
		(b) Is it described by functional changes? E.g. change of growth rate leading to loss of carbon sequestration?	Possible changes that are not acceptable – loss of habitat for rare species; loss of carbon storage; loss of rainfall interception	Loss of sales	Loss of productive area and production potential – leading to decline in wood supply
		(c) Are the boundaries precise or fuzzy?	Fuzzy	Precise	Fuzzy – no clear boundary between enough/not enough for many of the forest characteristics
		(d) Are thresholds thought to be involved?	Potentially; requires assessment	Potentially; requires assessment and context specific (e.g. attitude to financial risk and investment)	Not known
Step 4	Identify component of resilience amenable to target through policy or management choices	(a) Is there a resistance pathway? E.g. breeding disease resistant varieties	Yes –, e.g. Prevent arrival of EAB Breed for resistance to Ash dieback and deploy material Protect regeneration from herbivore damage to enhance evolved responses	Yes –, e.g. Biosecurity protocols to prevent infected plant material from being received into the nursery (and released by the nursery) Develop and breed resistant varieties	Yes, e.g. The forest could be made more resistant to wholesale windthrow by manipulation of age structure; this would confer some resistance to market downturn The forest could be made more resistant to disturbance by an individual host-specific disease by diversification of tree species The incursion of disease into the forest could be made less likely through biosecurity measures
		(b) Is there an adaptation pathway? E.g. Changing the tree species composition or the silvicultural management method	Potentially, e.g. Look for ash surrogates	Yes –, e.g. Adapt product range by changing the tree species raised and sold by the nursery Diversify the business so that the sole focus is not on raising and selling trees, e.g. increase the range of products by introducing non-tree plant stock	Yes, e.g. Recovery from disturbance could be enhanced by retaining regeneration potential (e.g. rotations which extend to coning age; control of deer browsing) Response to market downturn could be enhanced by encouragement of local/ alternative uses for timber
		(c) Is there a transformation pathway? E.g. Accepting a loss of some functions and identifying opportunities for new functions	No – woodland must still be present on the land and provide the same functions, even if the composition and structure is different	Possibly – stop raising trees and use the business premises for another tree-related venture	Potentially: Wholesale transformation to native woodland (avoiding some pests and diseases) or short-rotation forestry (avoiding high proportions of forest vulnerable to windthrow) would alter the risk profile and change the fundamental nature of the system

Continued

Table 4 *Continued*

Step	Action	Questions	Example 1: ecological	Example 2 – Business	Example 3 – Uncertain future
Step 5	Identify appropriate management actions	(a) Are there established techniques?	Yes – herbivore management and regeneration (encouraging propagule production and survival)	Yes – biosecurity; specific control measures; contingency planning; diversification of product lines	Yes, e.g. Good practice in design for species suitability (avoiding stressed trees which might be particularly vulnerable to certain pests/diseases) Spreading of age classes through response to windthrow and selection of felling dates
		(b) Are there techniques available for transfer from other settings?	Possibly; requires investigation, e.g. strategies and experience from Europe (Ash dieback) and North America (Emerald Ash Borer)	Yes –, e.g. from other types of nurseries	Potentially Biosecurity – general principles could be applied locally to minimise local threats Knowledge exchange with other managers wrestling with similar problems and who may have devised other solutions
		(c) Are new methods required?	Yes – for EAB	Yes – improved detection of pests and diseases on the nursery and in supply pathways	Yes, e.g. Silvicultural experience with new species on this type of site
Step 6	Monitor and learn	(a) Can adaptive management be practised? E.g. monitoring put in place to learn as implement	Yes , e.g. individual tree survival in face of disease	Yes – shared knowledge across nursery sector	Yes – design plan revision every 10 years approximately

to determine how far into the future we are looking for a system to persist in a particular state; this is likely to depend on the management objectives for the forest.

(c) Which functions or services are to be maintained?

Tree health and the forestry sector consist of many stakeholders (Marzano *et al*., 2015). As highlighted in our stakeholder discussions, the functions or services of interest are likely to vary depending on ownership, land management objectives and the stakeholders involved. Additionally, depending on the stakeholder's perspective, both the system of interest and the disturbance could be present at a range of smaller and greater scales and when multiple stakeholders are involved the system identity and functions and services of interest are likely to cross spatial and temporal scales.

Step 2: identify the threats to the system of interest The typical disturbance regime of the system (often referred to as natural disturbance) must be identified, in order to distinguish threats that are unusual and represent an unacceptable challenge to the system's ability to persist in its current or desired state (Walker *et al*., 2010). Disturbances can be short-lived; these tend to be natural 'pulse' disturbances such as fire or pest/disease outbreaks, or prolonged; these can be pulse disturbances transformed into chronic disturbances through human actions, which alter the frequency and magnitude of disturbance (Bengtsson *et al*., 2003). Many of our stakeholders viewed threats to forests as external pressures, and, likely due to the focus of the workshop, the majority identified pests and diseases as the primary concern. It was also noted that threats can interact (e.g. climate change and disease) and that they can occur within a particular spatial and temporal scale or cross several scales. Some also viewed current forestry practices as threats to resilience, e.g. loss of genetic and species diversity.

Step 3: Identify boundaries of acceptable change How much can the system change before it has either degraded to an undesirable state or become a new system state? There may be acceptable alternative states and if the system can range across a continuum of states, stakeholders must define when the continuum moves out of the acceptable range. Natural systems are quite often unable to return to the pre-disturbance state, requiring stakeholders to decide when the system has returned to a state that can be deemed a recovery. This can take many years, and an acceptable length of time for recovery to the pre-disturbance state must be selected. This is likely to be specific to the resilience 'of what', as some functions or services might be required to resume normal functioning very quickly, e.g. provision of wildlife habitat in a Special Area of Conservation.

Step 4: Identify component of resilience amenable to target through policy or management choices Resistance, recovery, transformation and adaptation represent possible pathways to increasing resilience of the system of interest. If specified resilience is required for a particular threat, it might be possible to develop management methods and techniques to increase the resistance of particular functions/services. In some cases, adaptation might be a more appropriate pathway to achieving recovery to the desired state when a disturbance has already affected a system.

Step 5: Identify appropriate management actions It will be important to identify a range of management methods, which might require developing new methods or adapting old ones. It is necessary to take into account how management plans might be affected by future disturbance or change of objectives, as well as not locking the system into one particular pathway, which could prove to be detrimental in future (Perrings, 1998; Ernstson *et al*., 2010). Management objectives held by different stakeholders are likely to influence responses to disturbance and the methods chosen for building resilience. There are risks and opportunities associated with forest management strategies. Our stakeholders discussed the pressure to diversify in order to increase resilience and how this might lead to planting non-native species, which was seen as unacceptable by some and inevitable by others due to climate change, problems with grazing animals, and the need to find species that can withstand other pressures. Diversification also posed problems in an economic sense as there was concern that planting species with unknown timber properties will lead to unviable crops.

Step 6: Monitor and learn The outcomes of the management should be monitored and assessed in order to integrate adaptive management into the resilience framework. Adaptive management is an experimental process of adapting management to changing environmental conditions by assessing the success of different management strategies and learning from the outcomes (Folke *et al*., 2002). The opportunity to learn from past mistakes was identified by some stakeholders as a particular benefit of the resilience concept. Monitoring the outcome of management for resilience was a crucial aspect for stakeholders as it allows successful strategies to be identified and implemented; this reduces uncertainty, which can limit public support and uptake of the resilience concept by private woodland owners/businesses.

Discussion

Defining resilience

The concept of resilience is topical but generally ill-defined across many disciplines, and there are few explicit guidelines on how to assess and manage for resilience in forests and the forestry sector (Rist and Moen, 2013; Newton and Cantarello, 2015). The complexity of the resilience concept and the variety of scales and interactions between environmental, social and economic dimensions of forest systems means that it is difficult to be both simple and specific. Our stakeholders were interested in implementing resilience for tree health and more broadly within the forestry sector but were uncertain how to do so and views differed in important aspects. There was divergence between stakeholders who were concerned with the resilience of forest systems and ecosystem services and those who thought of resilience in the context of their business. In addition, some considered management actions for resilience as pre-emptive, and others considered it to be post-disturbance; such actions would have very different consequences for practising resilience management with the former avoiding or deferring change whereas the latter embracing change.

Engineering resilience (with an emphasis on resistance) may be suitable in the strict context of pest and disease control for tree health over a fixed time period or where threats can be anticipated. However, social-ecological resilience might be a more suitable approach overall as forests are not present in a 'steady state' but move through a continuum of states via cycles of structural and compositional change induced by natural succession or management. This perspective may be more helpful when managing over the longer term. Additionally, in forest ecosystems, there is currently a lack of evidence for tipping points and gradual ongoing changes are generally more apparent (Reyer *et al*., 2015). These gradual changes play an important role in affecting the resilience of forests at a variety of spatial and temporal scales (Reyer *et al*., 2015) and represent the ability of a forest system to display a dynamic continuum of different states of varying resilience.

Evidently, constraining the choice of definition to engineering, ecological or social-ecological resilience may be unhelpful in the context of forest management where forest systems are likely to exhibit gradual shifts between various states. Furthermore, within a particular disturbance context, different aspects of resilience could be applicable. For example, within one forest area, several tree species might require management for pests and diseases, e.g. the focus might be on enabling the resistance or quick recovery of a particularly highly valued timber producing tree species, which would require engineering resilience, as well replacing a less highly valued tree species with a similar species to maintain wildlife habitat, which is better described through the adaptation or transformation process of social-ecological resilience. Note that these two positions suggest very different acceptances of change to the system of interest.

General descriptions of resilience in the current literature provide little steer when considering policy and practice. On the other hand, attempting to develop one short and specific definition of resilience comes with the risk of limiting future options, and a narrow formula for resilience action might be counter-productive leaving systems unable to respond to changes in societal values or threats over time, e.g. breeding resistant varieties reduces genetic or species diversity and can leave trees susceptible to new strains of disease. Rather than reworking the generally applicable and often vague definitions in the literature, we argue decision-makers and practitioners should concentrate on defining the various aspects of the system of interest in order to specify the focus of resilience management in a particular context. Application of the concept also needs to take into consideration the variety of stakeholders and potential users and their changing and sometimes conflicting requirements. Such a specification of the focal system will provide the basis for identifying management options.

Resilience implementation framework

Our resilience framework is based on evidence gathered from the literature and developed with stakeholder discussions. Similar approaches to defining and managing for resilience have recently been developed for other contexts, such as the US Climate Resilience Toolkit (US Government, 2015) and Resilience Alliance Workbook (Resilience Alliance, 2010). We recognize that the proposed framework requires further testing in a variety of settings. Nevertheless, we suggest it offers a flexible approach to the application of resilience in a number of different contexts presented by the tree health and the forestry sector, which may be adjusted as circumstances change or learning develops.

Implicit in this framework is the need for an assessment of resilience; many organizations (and associated decision-making processes) will expect to see some pre- or post-assessment to evaluate the impact of particular management actions. This will provide justification for carrying out particular operations and enable decision-making about whether to adjust future management actions. It will also allow good practice for resilience in particular contexts to be developed and shared to enable co-operation and learning in the forestry sector.

Since resilience is often defined as the magnitude of disturbance that can be absorbed before changing to another state (Holling, 1973), it is almost implicit in the definition that measuring resilience requires a threshold to be crossed or a change of state to have occurred before we can see a system's maximum capacity for absorbing disturbance (Carpenter, 2003). Resilience cannot be directly measured prior to disturbance (Carpenter *et al*., 2005), but the capacity for a system to be resilient could be measured through surrogate indicators, e.g. response diversity or functional redundancy (Elmqvist *et al*., 2003). However, there is considerable uncertainty about how to measure resilience in this way, due to a lack of empirical evidence to support the use of surrogates (Carpenter *et al*., 2005; Woodcock *et al*., 2015).

Options for assessing the resilience of forests will need to be carefully investigated to determine the most appropriate methods, and it is important to ensure a range of these are developed and made available, rather than a narrow set of pathways being encouraged or incentivized (Walker *et al*., 2010). Reliance on particular pathways or organizational structures which are responsible for resilience management should be discouraged, as this can lead to 'lock-in' of the system which prevents future adaptation in the face of disturbance (Perrings, 1998; Ernstson *et al*., 2010) and might imply greater certainty in the ability of these pathways to provide solutions than is the case. Identifying a suite of possible pathways that can be negotiated will also cater to the range of perspectives held by different stakeholders (Walker *et al*., 2010). Once these have been identified, it is envisaged that these can be used in combination with the Resilience Implementation Framework. This could provide the basis for an over-arching national strategy for resilience, to assess condition and target actions and also support local decision-making, to help managers understand and prioritize action.

Resilience and SFM

Resilience thinking is a new management model, which may provide a complementary approach to the ecosystem approach and adaptive management, the current strategies used to apply SFM (Rist and Moen, 2013). The concept of resilience provides a framework for achieving SFM in the face of various threats through building the capacity of trees and forests to withstand disturbances and thus continue to provide the environmental, social and economic functions and services for which they are valued (Rist and Moen, 2013). Walker *et al*. (2010) and Folke *et al*. (2002) state that resilience is critical for sustainable development as it underpins the ability of a system to develop whilst avoiding failure in a changing and unpredictable world. A particular benefit of resilience thinking is its potential to combine environmental, social and economic dimensions by considering the processes through which they interact and influence one another and how these are affected by disturbance; this is especially important in the context of natural resource management (Folke, 2006; Kinzig *et al*., 2006).

Conclusions

The concept of resilience has the potential to provide a complementary framework to the existing management paradigms of the ecosystem approach and adaptive management. However, definitions of resilience currently proposed in the literature are not specific enough to provide direction for policy and practice. We propose a structured approach to resilience management by defining the system, functions/services, threats and boundaries of acceptable change, and then the most relevant component of the resilience concept to target, i.e. resistance, adaptation, recovery or transformation. This offers a more comprehensive approach to understanding and managing for resilience in tree health and the forestry sector and can support practical forest management decision-making. Consistent with the call for a structured and iterative approach to management for resilience (Spears *et al.*, 2015), this framework can be applied in different contexts and scales and allows for the use of flexible management pathways which adjust as the uncertain future is revealed. However, testing of the framework in a variety of settings is desirable and could be achieved through using case studies.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

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