Forest Resilience

Part 2. Practical considerations

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provide a practical guide to achieving resilience.

We are facing a climate emergency and biodiversity crisis. Woodlands are part of the solution; appropriate tree planting can increase carbon capture and sensitive management supports woodland biodiversity. However, climate change and biodiversity loss also pose threats to our woodlands by undermining their ecological functioning, making them more vulnerable to pests and disease, and eroding their ability to deliver the many benefits that we derive from them. Action to increase forest resilience against these threats is more urgent than ever.

However, this is often easier said than done. There is a great deal of research and information about forest resilience, and applying it to individual sites can be challenging. In this article, we collate some practical advice for how forest resilience can be considered and implemented, and present some case studies to illustrate its application.

Resilience of what, against what?

Management actions to increase forest resilience take many forms. Deciding which actions are most appropriate at any given site will depend on the objectives for the woodland. For example, is the woodland managed for timber production, wildlife conservation, public green space, carbon storage, or flood mitigation? How might these objectives change in future? If there are multiple objectives, what are the relative priorities for different parts of the woodland? This sounds obvious but it is surprising how often the objectives for woodlands are poorly defined.

Once objectives for the woodland are clarified, the potential threats that might jeopardise their delivery can be assessed. For example, if commercial timber production is an objective, climate change might alter site suitability for some tree species and decrease future yield. Where wildlife conservation is a goal, intense browsing pressure from deer could be a problem. As each woodland has different objectives, so too will the combination and magnitude of threats differ. The idea of increasing forest resilience is to take action to lessen the impact of these threats on the delivery of the objectives (Figure 1).

The question 'resilience of what, against what?' is a useful reminder to think about the basics before making changes.

> "Asking the 'resilience of what, against what?' is fundamental."

The bigger picture

A woodland manager might have a narrow range of objectives and be predominantly concerned with only a few threats. However, it is always worth taking a step back to first consider the bigger picture. Increasing forest resilience is rarely just an environmental issue but will also be affected by economic and social factors. In addition to the known threats to our woodlands, such as climate change, and tree pests and disease, there will also be a range of unknown threats. Whilst we cannot know exactly what the future will hold, resilience makes woodlands more robust to new challenges and creates the potential for new opportunities.

As society changes it places different demands on our natural landscapes. Forestry operates over long timespans but innovation and technology can bring new possibilities and motivations. For centuries trees have been planted with one objective, such as firewood, shipbuilding, pit props or war, and harvested for entirely different purposes. Even just the last few decades have seen dramatic changes to forestry operations, with the development of more efficient machinery, reduction in manpower, and changes in pest populations. An account from Thetford Forest in the early 1950s illustrates this well, noting high red squirrel

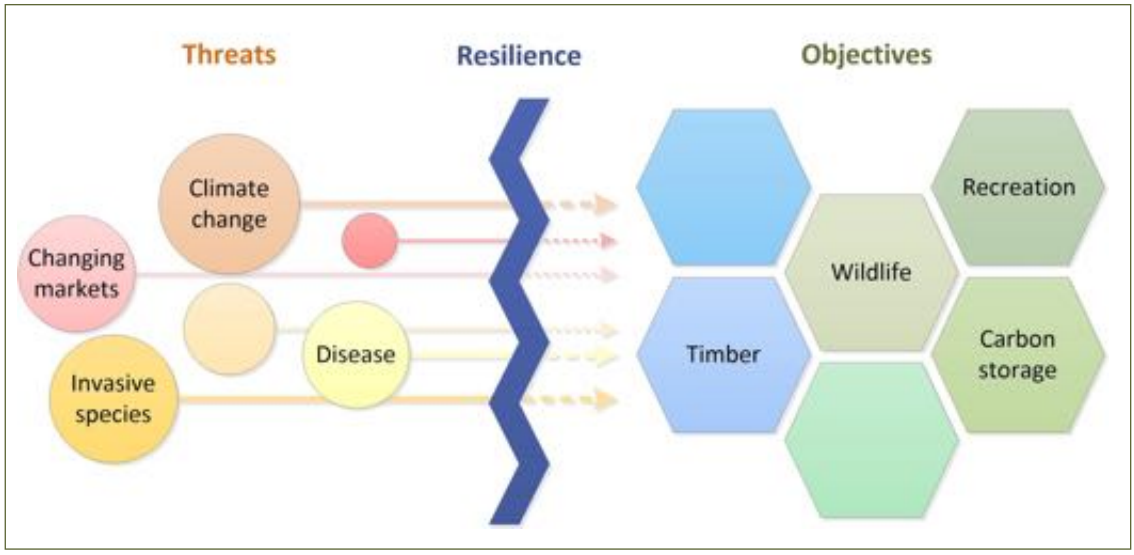


Figure 1. The resilience of what, against what? Defining the objectives for a woodland is a prerequisite to identifying issues that might threaten their delivery. Resilience actions aim to lessen the impact of these threats on the delivery of objectives.

populations, which were culled at the time (they are now locally extinct), and lack of deer pressure (there are now high densities of muntjac, fallow, roe and red deer) (Forestry Commission, 1952). These lessons from history remind us that circumstances can change dramatically over the lifetime of trees. Woodlands therefore need to be resilient in the long term. Defining woodland objectives too narrowly (for example by stating the type of timber production that is the goal) may be counter-productive. It is a good idea to keep future management options open as far as possible, keeping objectives adaptable and able to take advantage of new opportunities.

Identifying actions to increase resilience – some useful resources

Forest resilience principles can be applied in many different ways. The case studies at the end of this article illustrate how different approaches can be taken to similar problems. There is a great deal of information available on forest management but this can make it challenging to pinpoint the most useful resources. We provide an up-to-date list of resources with links and references in Table 1.

Good silviculture and management are fundamental components of resilience. This requires careful planning at the outset, supported by a woodland management plan. Whether creating a new woodland or assessing how to make an existing woodland more resilient, detailed site assessment is an essential first step. This informs the selection of tree species and silvicultural systems, which in turn can influence the objectives for a woodland. At all stages, from initial planning to ongoing management, actions must be taken to maintain ecosystem integrity, enhance ecological functioning and to protect tree health. In this section we briefly consider these aspects of forest management in turn; over the next several pages Table 1 lists practical tools and supporting guidance for the same topics discussed in the text.

Planning

Impacts of climate change

Mitigating against the consequences of climate change is a core focus of forest resilience. In addition to trends such as increasing temperatures and total rainfall, seasonal differences are likely to intensify, and extreme weather events such as droughts and storms will become more common. This will have a range of direct effects (such as changing site suitability for species) and indirect

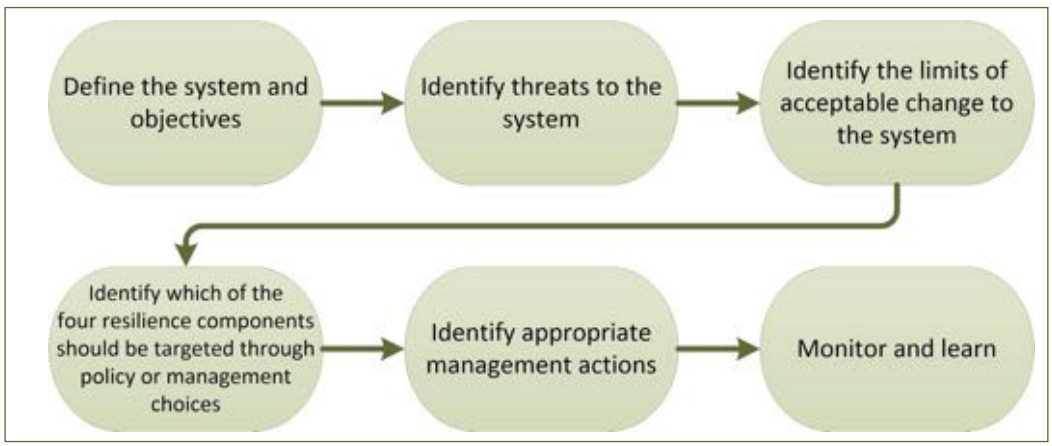


Figure 2. The six steps of the Resilience Implementation Framework (Fuller and Quine, 2016).

Table 1. Resources for implementing forest resilience *(This table continues over the next three left-hand pages.)*
Background colour indicates the type of resource: yellow – guides, advice or schemes, green – reference material (book, report, article), blue – online tool or database. The table is not designed to be exhaustive but rather to provide helpful starting points for each topic. Resources are freely available unless otherwise specified.

Category	Topic	Reference *(Type of resource)*	Description *Reference/website link*
Planning	Impacts of climate change	Managing England's woodlands in a climate emergency (2019) *(Forestry Commission guide)*	Practical, general advice on how to manage woodland to combat the effects of climate change. *https://www.gov.uk/government/publications/managing-englands-woodlands-in-a-climate-emergency*
		Climate Change Adaptation Manual (2020) *(Natural England and Royal Society for the Protection of Birds manual)*	Resource to support practical and pragmatic decision-making on adaptation to climate change in different ecosystems. Includes sections for each of the main broad woodland types and links to available resources and tools. *http://publications.naturalengland.org.uk/publication/5679197848862720*
		Climate Change Factsheet series (2021) *(Forest Research factsheets)*	A series of factsheets exploring the effects of climate change on trees and woodlands. *https://www.forestresearch.gov.uk/news/forest-research-launches-climate-change-factsheet-series/*
	Resilience Implementation Framework	Resilience and tree health: a basis for implementation in sustainable forest management (2016) *(Article)*	Review on the definition and understanding of resilience, including a six-step framework to help forest managers to implement resilience. *Fuller, L. & Quine, C.P. (2016) Forestry, 89(1):7-19. https://doi.org/10.1093/forestry/cpv046*
		Resilience Implementation Framework guide (2021) *(Forest Research guide)*	An accessible guide to help forest managers apply the Resilience Implementation Framework. *Boyd, F. et al. (2021) Forest Research.*
	Woodland management plan guidance and funding	Create a woodland management plan *(UK government webpage)*	Guidance on creating a UK Forestry Standard compliant management plan, including examples and a template. *https://www.gov.uk/guidance/create-a-woodland-management-plan*
		myForest *(Sylva Foundation online tools and resources)*	Online tools and resources for woodland management. *https://myforest.sylva.org.uk/home*
		Countryside stewardship woodland support grants *(UK government webpage)*	Funding for woodland improvement for biodiversity or water benefits, restocking following tree health issues, removal of rhododendron, woodland management planning and woodland creation. *https://www.gov.uk/government/collections/countryside-stewardship-get-paid-for-environmental-land-management#woodland-support-grants*
Site assessment	Soil	The identification of soils for forest management (2012) *(Forestry Commission field guide, £17)*	A field guide for rapid identification of forest soils using the Forestry Commission classification system. Kennedy, F. Forestry Commission Edinburgh. *https://www.forestresearch.gov.uk/research/the-identification-of-soils-for-forest-management/*
		Ecological Site Classification (ESC) Field Survey Pack *(Forestry Commission guide)*	A field survey pack with identification guides and recording forms for soil, humus form, and indicator vegetation. Designed for use alongside ESC. *https://www.forestresearch.gov.uk/documents/2110/escfsp.pdf*
		ESC Woodland Species Guide (2017) *(Royal Forestry Society guide)*	A guide for identification of common plant indicator species (species that are linked to particular soil characteristics). Designed for use alongside ESC. *Coltman, R. & Todd, A. Royal Forestry Society. https://www.rfs.org.uk/media/429098/compilation-booklet-05-09-with-10-missing-lq.pdf*
	Climate	Forest Research Climate Matching Tool *(Forest Research online tool)*	A tool that illustrates the likely effects of climate change for any location in the UK, by showing locations that currently have climates comparable to future UK site conditions. *https://www.forestresearch.gov.uk /tools-and-resources/climate-matching-tool/*

consequences (such as causing stress to trees that makes them more vulnerable to disease). While we have good models that can project climate change scenarios, there is also great uncertainty. Table 1 lists some resources that summarise the implications of climate change on UK forests and provide management recommendations.

Resilience Implementation Framework
A review of the definition and understanding of resilience in tree health and forestry has identified four main resilience components: resistance, recovery, adaptation and transformation, and a six-step Resilience Implementation Framework (Fuller and Quine, 2016; Figure 2). Forest Research has produced a user-friendly Resilience Implementation Framework guide (Boyd et al., 2021), which leads the user through defining resilience objectives for their site and identifying management actions to increase resilience. The Framework can be used to understand how to increase the resilience of other systems too, such as a nursery or forestry business.

Woodland management plan guidance and funding
The best time to consider objectives and threats is during the management planning process. This starts with the creation of a woodland management plan, including elements such as a plan of operations, ideally based on the UK Forestry Standard (the Forestry Commission provides a template for this). Woodland management plans work best when viewed as working documents that provide the backbone to management decisions but also evolve with changing circumstances. Depending on the UK country, funding may be available to help produce a plan, it can be linked to felling licences and it may even be a prerequisite for other funding applications.

Site assessment

A full understanding of the environmental conditions of a site is necessary for the selection of well-suited species and silvicultural systems. Site assessment also helps in understanding likely climate change impacts, interpreting tree health symptoms and planning successful tree establishment (including for natural regeneration). A site assessment should include an appraisal of the landscape features, slope and aspect, soil and climate.

Soil
Soil moisture, nutrient content, depth and texture fundamentally affect the viability of alternative woodland types. The most useful tool for soil assessment is a humble spade! Alternatively, soil augers can increase the rate at which the full soil profile can be assessed. Vegetation identification is also a good indicator of soil characteristics and can be particularly useful for understanding how site conditions vary spatially. A range of guides are available to help conduct and interpret local site assessments (Table 1).

Climate
Climate is a major determinant of tree species suitability, especially temperature and rainfall. Seasonal variation and windiness are also important. Detailed climate and weather records are available from the Met Office. The Forestry Commission's Ecological Site Classification tool (ESC) models these variables across the UK. Climate change will alter these factors in different ways across the country so it is important to be familiar with local site projections. Forest Research's Climate Matching Tool provides a visual interpretation of what future climate might look like for any location in the UK using comparisons to current

Accurate surveying of soils is fundamental. This clay heavy brown earth on top of the north downs is well suited to growing sweet chestnut although some models predict suitability may decline by 2080. (Photo: Rob Coventry)

Table 1. continued

Site assessment cont.	Climate cont.	UK Climate datasets *(Met Office data)*	Range of datasets to explore climate statistics for different regions. Modelled data are also available at fine resolution (1km squares) but more advanced data processing skills are required to download and view it. *https://www.metoffice.gov.uk/research/climate/maps-and-data/data/index*
		Ecological Site Classification tool (ESC) *(Forestry Commission online tool)*	An online tool that uses site data (soil type, windiness etc) to generate tree species suitability predictions under current and potential future climates. ESC default soils maps are for strategic level use so local soil information is essential. *https://www.forestresearch.gov.uk/tools-and-resources/ecological-site-classification-decision-support-system-esc-dss/*
Species	Species Selection	Ecological Site Classification tool (ESC) *(Forestry Commission online tool)*	See 'Climate' section above.
		Royal Forestry Society Species Profiles *(Royal Forestry Society short articles)*	15 papers about less familiar species, e.g. 'The redwoods and red cedar', 'Macedonian pine', 'Noble hardwood alternatives to ash'. *https://www.rfs.org.uk/learning/forestry-knowledge-hub/forest-resilience/alternative-tree-species/*
		Silviculture of Trees Used in British Forestry (2019) *(Book, £95)*	Information on tree species suitability for different purposes, including climate and soil requirements and other silvicultural characteristics. *Savill, P. CABI. 3rd edition.*
		Tree species database *(Forest Research online database)*	Information on over 60 tree species that are either widely grown in British forests at the present time or which could play an increasing role in the future. *https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/*
	Species provenance	Genetic considerations for provenance choice of native trees under climate change in England (2019) *(ForestryCommission, Natural England and Woodland Trust Policy Advice Note)*	Practical, take-home messages from research evaluating the evidence aound provenance choice and adaptation to climate change when planting native woodland. *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/809733/Policy_Advice_Note_Final180619.pdf*
		Provenance variation of emerging species *(Forest Research webpage)*	Summary of provenance recommendations for eight emerging conifer species. Includes links to further reference material. *https://www.forestresearch.gov.uk/research/provenance-variation-emerging-species/*
		Forest Research Climate Matching Tool *(Forest Research online tool)*	See 'Climate' section above. *https://www.forestresearch.gov.uk/tools-and-resources/climate-matching-tool/*
Silvicultural systems	Species mixtures	Establishing robust species mixtures (2020) *(Quarterly Journal of Forestry article)*	Describes a method to design robust mixtures of species at the establishment phase. Includes a methodology for determining a compatibility score of species combinations. *Kerr, G. et al. Quarterly Journal of Forestry, 114(3)*
	Continuous cover forestry	Continuous cover silviculture *(Forest Research webpage)*	Information, tools and research on various aspects of CCF. *https://www.forestresearch.gov.uk/research/continuous-cover-silviculture/*
		Managing continuous cover forests (2008) *(Forestry Commission Operational Guidance Booklet)*	Practical guidance for continuous cover forestry. *https://www.forestresearch.gov.uk/research/managing-continuous-cover-forests/*
		Successful Underplanting (2016) *(Forestry Commission guide)*	Practical guidance for underplanting. *https://www.forestresearch.gov.uk/documents/1512/UnderplantingGuideVersion10_11October2016.pdf*

climates elsewhere in Europe and the Pacific North West of America (discussed in detail in Forest Resilience Part 1; Tew et al., 2021).

Species and provenance selection

Species selection

Following a detailed site assessment, an appropriate combination of tree species and silvicultural systems can be selected. Whether planting a new or restock site, underplanting or using natural regeneration, the choice of species will heavily influence the likely future health and yield of the stand. This represents a pivotal moment in setting the future trajectory of a forest system, with obvious implications for long-term resilience. In addition, the characteristics of a species will determine its suitability to different silvicultural systems. There are many useful resources to assist with species selection. In particular, ESC is a commonly used, helpful online tool that predicts species suitability based on modelled climate and soil data. It can be supplemented with locally collected site assessment data, which is strongly recommended. For example, the baseline soils map in ESC has a coarse resolution that fails to capture local variation; this can give misleading species suitability results so adding local data is an important refinement.

> "It is important in future that planning and management is anticipatory and proactive instead of reactive."

Provenance choice

Once appropriate tree species have been selected for a site, the next important step is to identify suitable provenances (seed sources). For resilience, a wide genetic base is very important, as this increases the capacity for adaptation to future conditions; fortunately, genetic variation of tree populations is inherently high (Whittet et al., 2019). In choosing provenances there are a range of options; locally sourced seed will be adapted to local conditions, but seed transferred from further south (assisted migration) may be better able to tolerate future climatic changes. In general, a portfolio approach is recommended, including a mixture of planting stock from local and more southerly provenances alongside natural regeneration, with the final ratio dependent on management objectives and approach to risk. Choosing a range of provenances increases forest resilience by spreading the risk associated with each provenance choice.

Silvicultural systems

Species mixtures

The UK would naturally have mosaics of tree communities (Rackham, 1992). In any part of the mosaic, one or two species might dominate but several others would be present in smaller numbers. This is reflected in the National Vegetation Classification of woodland types (Hall et al., 2004). Monocultures and single-storey forests are generally not a natural stand type for the UK's temperate, maritime climate. Intensive monoculture production forests currently provide an important timber supply but these systems are vulnerable to disturbance or changing conditions, which can result in catastrophic damage or loss across the whole system. In contrast, species mixtures usually have greater resilience because the diversity of species spreads risk (as with the portfolio approach to provenance selection); this is particularly important given uncertainty around future conditions and how different species might adapt.

In addition to the beneficial 'dilution' effect of mixtures, they can also exhibit overyielding (whereby there is greater overall productivity compared to monocultures because different species make use of different resources) and stabilise stand productivity through time (as species respond differently to stress events) (Pretzsch, 2017; Bauhus et al., 2017). Increasing tree species diversity frequently reduces the effects of specialist pests and diseases (although not necessarily for generalist pests and diseases) (Bauhus et al., 2017). On average, mixtures are more resilient to drought than monocultures, although effects vary and are influenced by factors such as the species identity and site characteristics (Grossiord, 2019; Pardos et al., 2021).

Continuous-cover forestry

Continuous cover forestry (CCF) promotes a mix of age-classes, canopy height, tree diameter sizes and tree density through regular, targeted thinning and the use of natural regeneration. Again, a diverse structure spreads risk and provides insurance should a particular structural component struggle or fail, so CCF tends to be more resilient than even-aged systems. CCF can be implemented in both monocultures and mixtures, and it may be a natural outcome of interventions to increase species diversity. Over the longer term, CCF management may be more

Table 1. continued

Silvicultural systems cont.	Continuous cover forestry cont.	Continuous Cover Forestry (2017) *(Pro Silva Silviculture guide, €10)*	Guidelines on implementing continuous cover forestry and close to nature forestry management practices *https://prosilvaireland.com/welcome-to-pro-silva-ireland-the-authority-of-continous-cover-forestry-in-ireland/information-booklets/*
		Encouraging Greater Use of Continuous Cover Forestry *(Quarterly Journal of Forestry articles)*	Part 1: Stand and site considerations *Mason, W. (2020) Quarterly Journal of Forestry, 114(4)* *& Mason, W. (2021) Quarterly Journal of Forestry, 115(1)*
	Forest Development Types	Forest Development Types: an essential tool for diversifying stands in Britain (2021) *(Quarterly Journal of Forestry article)*	Introduction to Forest Development Types, describing their benefits and application. *Haufe, J. et al. (2021) Quarterly Journal of Forestry, 115(2)*
Functioning ecosystems	Soil protection	Protecting the Environment during Mechanised Harvesting Operations (2005) *(Forestry Commission Technical Note)*	Technical note covering site planning, machine selection, brash mat construction and maintenance, drain and watercourse crossing, forest road approaches and roadside stacking. *https://www.forestresearch.gov.uk/research/protecting-the-environment-during-mechanised-harvesting-operations/*
		Guidance on cultivation and UKFS compliance for application in England (2021) *(Forestry Commission Operations Note)*	Operational note for England on the use of cultivation and a six-step process for determining which technique, if any, is the most appropriate. A full UKFS Technical Note (covering all countries) is under consideration. *https://www.gov.uk/government/publications/guidance-on-cultivation-and-ukfs-compliance-for-application-in-england-operations-note-53*
		Soils Cultivation on Afforestation Sites (2021) *(Royal Forestry Society YouTube video)*	Webinar recording covering soil cultivation and an excellent introduction to soils identification. *https://www.youtube.com/watch?v=jyxPyWMPFYk&t=90s*
	Species management	Manage threats to woodland: destructive animals, invasive species *(UK government webpage)*	Information on managing deer, feral wild boar, grey squirrels and other invasive species. *https://www.gov.uk/guidance/manage-threats-to-woodland-destructive-animals-invasive-species*
		Non-native species secretariat *(Webpage and database)*	Resources and guidance about biosecurity and management of non-native species. Includes a searchable database for information about non-native species. *http://www.nonnativespecies.org/home/index.cfm*
		Managing and controlling invasive rhododendron (2006) *(Forestry Commission Practice Guide)*	Practice guide covering surveying and monitoring of a site, and selecting and implementing control techniques. *https://www.forestresearch.gov.uk/research/managing-and-controlling-invasive-rhododendron/*
		Controlling grey squirrels in forests and woodlands in the UK (2019) *(UK Forestry Standard Technical Note)*	Updated information on methods of grey squirrel control in response to changes in legislation as well as recent developments in control methods and trap designs. *https://www.forestresearch.gov.uk/research/controlling-grey-squirrels-forests-and-woodlands-uk/*
		Deer Initiative: best practice guidance *(Deer Initiative webpage)*	Best practice guidance on deer management and how to carry it out effectively; how to safeguard personal and public safety and animal welfare; and how to maintain legal requirements. *https://www.thedeerinitiative.co.uk/best_practice/*
		Advice from Forestry Commission Deer Officers	Webpage with contact details for Forestry Commission Woodland Officers, who will forward enquiries to Deer Officers as appropriate. Deer Officers can give advice on deer management and establishing landscape-scale initiatives. *https://www.gov.uk/government/organisations/forestry-commission/about/access-and-opening#area-offices*

economical as well as more resilient, especially as the threats associated with climate change increase in intensity and the need to maintain forest microclimates and take advantage of natural regeneration becomes more important.

Forest Development Types

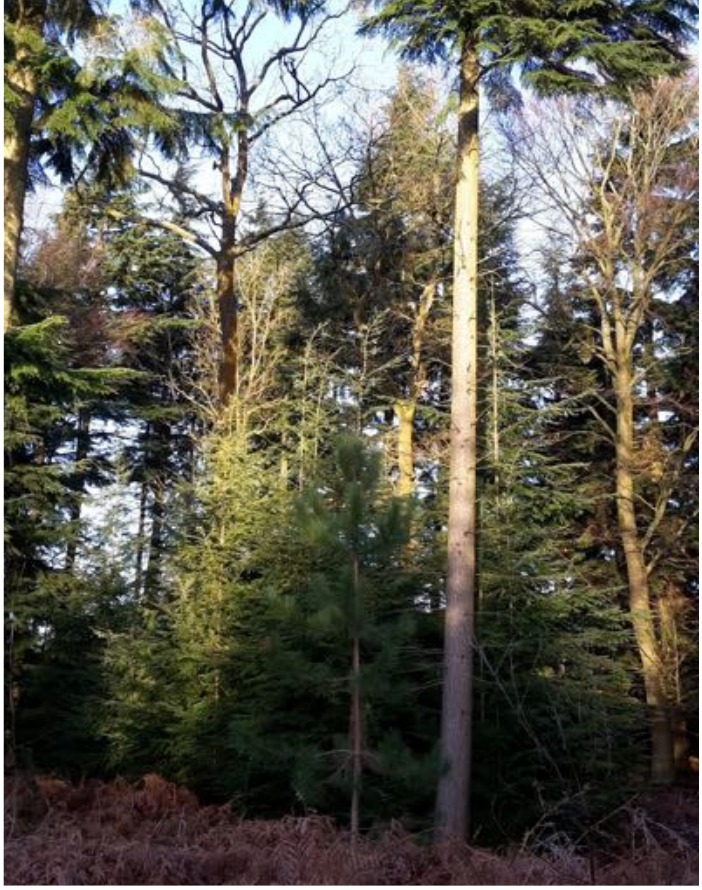
In diversifying stand structures and species compositions to achieve greater resilience, the concept of Forest Development Types is particularly useful in characterising different woodland management options and setting the long-term vision for the development of a forest stand. Forest Development Types have been used widely in Europe and a new classification system has been developed for the UK, including more than 60 Forest Development Types, introduced in detail in another article in this *Quarterly Journal of Forestry* issue (Haufe et al., 2021). The system can be used to compare and choose between different site options; for example, FDT 2.1.1 describes a Scots pine even-aged monoculture, whereas FDT 2.1.5 describes a Scots pine and oak multi-aged mixture with a small component of additional species. The accompanying information for each of the Forest Development Types gives guidance on which site types are suitable (e.g. climate and soil requirements), how they can deliver management objectives and advice on establishment and management. This helps both in selecting an appropriate silvicultural trajectory for a site and in understanding how to transform stands to reach this vision.

Ecosystem integrity

Ecosystem integrity is fundamental to the maintenance of functioning, resilient woodland systems. Increasing resilience in the face of unpredictable threats such as climate change often involves a range of precautionary actions to spread risk but many issues require direct management, for example soil protection and biodiversity conservation. Biodiverse habitats are more robust, productive and stable than impoverished ecosystems (Tilman et al., 2014).

Soil protection

In recent decades there has been a dramatic increase in the use of large, efficient machinery that improves harvesting productivity. However, compaction and rutting of vulnerable and waterlogged soils can cause serious damage. This affects the functioning and resilience of the whole ecosystem. For example, mycorrhizal fungi increase



A patch of regeneration being recruited to the mid-storey in a mixed CCF system at Alice Holt forest in Hampshire. (Photo: Rob Coventry)

forest resilience by providing water to trees in times of drought and combating pathogen attacks, but compaction greatly hinders soil fungal activity (Spencer, 2018). Compaction restricts oxygen and water movement through soil, limiting its supply to soil organisms and plants and inhibiting tree regeneration and long-term productivity (Cambi et al., 2015). Rutting can lead to run-off and erosion, depleting soil nutrients and polluting downstream watercourses. Limiting machinery size, using different extraction methods and restricting harvesting operations to appropriate weather windows is central to maintaining ecosystem integrity.

Ground preparation for new woodland creation sites and for restocks can also damage soils. Even in the face of browsing and weed growth problems, it is important not to prioritise ease and speed of establishment over long-term soil health. Cultivation should cause as little ground disturbance as possible, particularly on soils where carbon may be released.

Species management

Some species are damaging to biodiversity and ecosystem functioning because they dominate their environment to the detriment of other species. This is often a consequence of human interference, either directly (such as the introduction of invasive or alien species) or indirectly (such as the removal of predators leading to high prey population densities).

Table 1. continued

Functioning ecosystems cont.	Species management cont.	Preventing mammal damage to trees and woodland *(Forest Research webpage)*	An overview of control methods and links to further information. *https://www.forestresearch.gov.uk/research/preventing-mammal-damage-to-trees-and-woodland/#tablea*
Biosecurity		Plant Healthy Certification Scheme	A voluntary biosecurity certification scheme for nurseries and horticultural, arboricultural and forestry businesses to help protect them, and the natural environment from destructive plant pests and diseases. *https://planthealthy.org.uk/certification*
		DEFRA: The UK Plant Health Information Portal *(Web-based portal)*	Contains resources on biosecurity, risk assessment, contingency planning, and reporting and managing threats to plant health. *https://planthealthportal.defra.gov.uk/*
		TreeAlert (Forest Research webpage)	A web-based form to report signs of tree pests and diseases to Forest Research. *https://www.forestresearch.gov.uk/tools-and-resources/tree-alert/*
		Forestry Commission: Prevent the introduction and spread of tree pests and diseases *(UK government webpage)*	Information on measures you can take to prevent tree pests and diseases from establishing and spreading, including putting together a biosecurity kit. *https://www.gov.uk/guidance/prevent-the-introduction-and-spread-of-tree-pests-and-diseases*

Invasive species are plants and animals outside their natural range that have been released into wild habitats, either intentionally or inadvertently. They cause significant environmental, social and economic damage (Defra, 2015). For example, the grey squirrel spreads disease and outcompetes the native red squirrel and causes extensive damage to broadleaved trees (Gill, 2019). In UK forests rhododendron and gaultheria rapidly spread and dominate the understorey. Climate change will exacerbate the impact of some invasive species as they expand their range to higher altitudes and more northerly latitudes.

High densities of deer (including non-native muntjac, fallow, Sika and Chinese water deer, and native red and roe) are a problem across much of the UK. They have no natural predators and benefit from changing farming practices by feeding on autumn-sown cereal crops through the winter (Eichorn et al., 2017; Fuller and Gill, 2001). The intensity of deer browsing dramatically alters woodland species composition and structure by removing understorey vegetation and creating characteristic browse lines. Natural regeneration can be inhibited and tree planting may be unviable without protection. Overall, biodiversity is depleted and ecosystem functioning is weakened (Spake et al., 2020). Management options include exclusion (for example fencing) or direct population control but excessive numbers of deer is a major problem.

Biosecurity

Pests and disease are one of the greatest threats to UK forests. Taking steps to reduce the risk of introducing or spreading pests and diseases must go alongside management that minimises impact should they arrive in future. Specifying biosecure planting stock that has been grown in the UK from seed of a known and registered source is strongly encouraged; the new Plant Healthy certification scheme for businesses is a useful mechanism to ensure this (Table 1). Cleaning vehicles, equipment and personal protective equipment (PPE) between sites is essential in limiting the spread of harmful pests and diseases. Additionally, being alert to new signs of pests or pathogens and reporting this promptly, particularly in areas where there is no existing record, is vital in containing spread and preventing more widespread damage. Biosecurity is a collective responsibility across the forestry sector.

Conclusion

Implementing actions to increase forest resilience is challenging because of the diverse and complex set of interrelated issues that currently threaten woodlands. However, action is urgently required (Tew et al., 2021). The case studies accompanying this article show how forest resilience principles can be applied in response to a major disease outbreak, but it is important in future that planning and management is anticipatory and proactive instead of reactive. Asking the 'resilience of what, against what?' is fundamental. There is a wide range of resources and guidance available that can then help translate theory into practice; Table 1 provides a useful starting point.

There is much to consider. In some cases, particularly

Case studies - increasing resilience following disease

Here we present two examples of alternative responses to the infection of Corsican pine with *Dothistroma* needle blight. Both case studies are from the nation's forests, managed by Forestry England. *Dothistroma* needle blight is caused by a fungal pathogen and leads to needle loss, dramatic decreases in tree growth and sometimes death (Brown and Webber, 2008). In 2006 a ban on new Corsican pine planting was introduced across the nation's forests. The species diversification that followed has increased resilience to future disease outbreaks, climate impacts and other threats. Planting alternative species presented a host of challenges but also encouraged innovative thinking and catalysed wider action.

Sherwood, Central Forest District

Following discovery of *Dothistroma* needle blight in Sherwood, an ambitious programme was launched to transition 6000ha of Corsican pine to alternative species over a 20-year period. The Forestry England team knew that a novel range of species would require different silvicultural techniques. The existing system had relied on rotational clearfell, which created restocking conditions that suited pioneer species. However, alternative successional species that would better suit future climates were not so successful in large open restock coupes, as they tended to have intermediate shade requirements and were less tolerant of the late frosts that are common in this part of the country. From 2012 a range of new restocking techniques were piloted, starting with planting in extraction racks and progressing to strip felling; strategies were adapted based on observations and experience. A technique using strip felling of 50% of the crop (e.g. felling three rows and leaving three rows) has now been used successfully for five years.

Changing to a different silvicultural system presented resourcing and planning challenges but created new opportunities in turn. Shifting from the rotational clearfell system to a more complex felling and restocking procedure was expected to be significantly more expensive. The team therefore switched to a system of planting as soon as possible after harvest (within about six weeks), removing the need to do pre- and post-planting weeding and practically eliminating herbicide use – a major environmental success. The programme generated a substantial area of new planting every year in addition to the existing restock schedule, so they also moved to year-round restocking, which they have found to be just as successful as using the conventional, limited winter planting season. The stocking density was increased to reduce the labour needed for beat-up plant replacements. New machinery was purchased to optimise ground preparation effort (a model based on mulching followed by scarifying), enabling the team to plan their planting programme more efficiently and react quickly to disruptions such as unfavourable weather. They have also found that mulching immediately after harvesting seems to be effective in removing the breeding material for pine weevils, resulting in very little ongoing damage from the pest. Overall, the team has been able to reduce their restock costs compared to the traditional clearfell system, delivering greater business, as well as silvicultural, resilience.

Western red cedar established in an extraction rack as part of early restocking trials, Central Forest District, Forestry England. (Photo: Andy Powers)

The transition is ongoing but has so far been a great success. Across all its restock sites, Central Forest District now plants 42 different tree species, carefully selected to suit site conditions and objectives, using a range of silvicultural techniques. This diversity confers greater resilience to environmental change and simultaneously benefits biodiversity by increasing habitat diversity. The team have found that willingness to experiment and continuing adaptability is fundamental. Ideas must be thought through logically and carefully, acted on quickly, and then adapted in line with new learning.

Thetford Forest, East Forest District

In Thetford Forest, *Dothistroma* needle blight has affected approximately 8000ha of Corsican pine since the first infections in the early 2000s. Evidence suggests that infection was exacerbated in young stands where close tree spacing limited air flow and created humid conditions that favoured the pathogen, and so a programme of heavy thinning was initiated to mitigate this impact. Opening the canopy presented the opportunity to underplant the Corsican pine stands, making use of the shelter and microclimate provided by the existing trees to establish alternative species less suited to open restocks. Ten species were selected initially based on their expected future climate suitability and resistance to frost and drought (which are locally significant risks).

Over time, the underplanting strategy has evolved. For example, intimate mixtures with species distributed randomly are now increasingly used instead of the original block planting technique. Unsurprisingly, some species have performed better than others, with some being discontinued from the planting programme (such as Weymouth pine), whereas other species have coped well with droughts and browse pressure (such as Douglas fir and western red cedar). Currently 13 species (a combination of seven main species already well-known to forestry and six minor species) are used in the underplanting. The order and arrangement of rows that are thinned and underplanted has been refined to accommodate forestry operations, and different types of ground preparation have been trialled. The underplanting programme is now successfully converting 200-220ha of habitat per year from an even-aged monoculture to diverse, multi-structured stands.

However, the scale of change required over the whole forest landscape has far-reaching consequences. The repercussions from *Dothistroma* needle blight have prompted the creation of the Thetford Forest Resilience Programme, with an aim to create a 50-year Concept Plan for Thetford Forest. This will describe the long-term vision for what a resilient future forest will look like. The overall management objective for the nation's forests is to deliver a wide range of benefits for people, nature and the economy. Therefore, the main challenge in designing the Concept Plan is the diversity of issues that need to be considered and the complexity with which they interrelate. To address all the objectives and potential threats, the Resilience Programme has established 17 workstreams, covering everything from tree species choice, silviculture and deer management to recreation, wildlife conservation and heritage. These workstreams are being tackled by a large team of staff encompassing a variety of roles in the East Forest District. This inclusivity is fundamental to the Resilience Programme, bringing together different expertise, perspectives and experience to design a collaborative vision for the future forest.

By establishing a formal programme, the East Forest District has recognised the scale and importance of increasing resilience across a large forest landscape. Although ambitious, it is bringing clarity and structure to a highly complex set of issues and will yield important information and guidance in years to come.

where there are diverse objectives and threats, planning for forest resilience will need to be extensive (such as in the Thetford Forest Resilience Programme, see case studies box). However, time invested now will pay dividends in future. Forward-thinking decisions will enable forests to survive and hopefully thrive under future conditions, delivering against objectives in a more reliable way and ultimately saving time and money.

Different actions will be appropriate in different places, according to site-specific combinations of objectives and threats, and based on site characteristics. Above all, our case studies demonstrate the importance of adaptability. We should be willing to try new techniques and evolve strategies with experience, taking new opportunities as they arise. Recording and sharing our experiences and observations is crucial, increasing our collective knowledge base and confidence to act.

It is an exciting time to be involved in forest management. Foresters have always experimented and adapted to changing times and conditions; new thinking about forest resilience is a natural continuation of this.

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