RestREco

Practitioners' briefing

# Managing for ecological complexity



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# Overview

– Climate change, biodiversity loss and changing environmental conditions make it increasingly difficult to restore ecosystems to a historical reference state.

– The Restoring Resilient Ecosystems project (RestREco) has examined complexity and resilience as targets for nature recovery in woodlands and grasslands.

– Ecosystems that are more complex are generally more resilient, multifunctional and better able to adapt to disturbance and environmental change.

– Complexity is the number of components within an ecosystem and the connections between them.

– Components include species, habitat features, vegetation layers and trophic groups while connections include species interactions such as pollination, feeding relationships and habitat connectivity.

– Complexity is multidimensional and cannot be simplified to one indicator.

– Research has identified structural variation, species and functional diversity and complex interaction networks as important for multifunctionality and resilience.

– Managing for complexity focuses on supporting ecosystem structure, ecological processes and interactions over recreating specific species compositions.

– Management should aim to increase structural variation, promote species diversity, support ecological processes and reduce pressures.

– For woodlands, practitioners can promote structural complexity through variation in tree species, age, size and density using traditional management techniques, and through rides, glades and woodland edges.

– Maintaining dead wood and veteran trees adds structure and provides microhabitats for species, promoting adaptation and resilience.

– Supporting diverse plant-herbivore interaction networks across woodland landscapes promotes woodland ecological function, resilience and stability.

– For established grasslands, managers can encourage plant and structural complexity through low-intensity grazing, or by using species-rich seed mixes on grassland regeneration sites.

– Structural complexity in grasslands through variation in vegetation height, patches of bare ground and scrub cover can promote resilience and function.

– Supporting pollinator-plant interaction networks can increase ecosystem stability and robustness to environmental change.

– Adaptive management means accepting change and uncertainty and focusing on maintaining ecological function, resilience and adaptive capacity.

– Monitoring action outcomes and ecological change is vital to inform and adjust management over time.

– Resist-Accept-Direct (RAD) is a framework of approaches to resist unwanted change, accommodate unavoidable change or actively direct ecosystems towards desired future conditions.



# Introduction

This document is supplementary to policy briefing, 'Why ecological complexity matters', which details the findings of the Restoring Resilient Ecosystems (RestREco) partnership project: a four-year Natural Environment Research Council (NERC) funded project that reconsidered the aims of ecosystem restoration. 'Why ecological complexity matters' also places RestREco findings in the context of wider research. Focusing on UK woodland and grassland habitats, the project examined complexity and resilience as targets in relation to nature recovery.

This guide for practitioners (Managing for ecological complexity) brings together findings from the project, other research and current best practice into an approach to ecological restoration that supports ecosystems that are functional and resilient to change and introduces the application of adaptive management.

## Why we need a new approach

Restoration efforts to date have largely focused on targeting the restoration of ecosystems to a pre-disturbance, historical reference state including a specific suite of species. However, climate change is altering environmental conditions, leading to irreversible changes in species distribution patterns and abundances, habitat structure and water availability. This makes it challenging to define or maintain fixed species assemblages and historic states. At the same time, the unpredictable nature of climate change means it is difficult to determine how ecosystem structure and function will be affected. As complex systems show greater multifunctionality and resilience, managing and restoring for complexity could be the way forward.

Complexity is already recognised in a number of existing best practice documents – Natural England, the Woodland Trust and Forest Research, for example, incorporate complexity-related features into guidance for woodlands, grasslands and other habitats, and complexity is informing the work of many in the conservation sector.

## About complexity

Complexity is defined as "the number of components in a system and the number of connections among them".[1] Components include vegetation heights/height classes, species, trophic levels, insect biomass and ecotones. Connections include species interactions such as mutualism and herbivory, feeding relationships and connectivity between habitat patches.

Complexity is multi-dimensional and cannot be reduced to one metric.  Research from RestREco has identified multiple key aspects of complexity that are important for the success of restoration efforts, depending on habitat type.



## Woodlands

Woodlands provide an estimated £2 billion of vital ecosystem services including provisioning of timber, building materials and fuel; climate regulation through carbon sequestration; boosting air quality through removal of particulates; flood and soil erosion mitigation and recreational value.[2, 3] The ability of woodlands to be multifunctional is dependent on its complexity: greater biodiversity and heterogeneity means the species and features that provide these services are more likely to be present.[1]

Two aspects of complexity which are the most important for woodlands are structural complexity and network complexity. Structural complexity describes variations in the physical arrangement of a woodland including native tree and shrub species richness; variations in tree height, trunk diameter and age; areas of open space; niches and microclimates; and dead wood and veteran trees. Network complexity is a measure of the diversity of inter-species interactions including herbivory, pollination, predation and mutualism.

## Structural complexity

Structural complexity boosts plant and animal diversity. Woodlands with uneven tree sizes (for example, heights or trunk diameters) have more woodland specialists and generalists, more insect biomass, abundances, greater genus and functional richness, and support small mammal diversity.[5, 6, 7, 8] Structural complexity and reduced herbivory pressure lead to variations in microclimate and niches that can be exploited by more species.[8]

Results from RestREco demonstrated that more structurally complex woodlands had more complex soundscapes, characterised by high temporal variation and a less even distribution of sound energy, suggesting that acoustic monitoring could be used to monitor ecological complexity.[9]

There is evidence that structurally complex woodlands are more resilient. Fungal infection, disease spread and associated tree mortality is reduced or slowed by increased tree species richness, genetic diversity and variations in tree density (longer distances between pathogen hosts).[10] Microhabitat variation in dead wood or veteran trees support functionally diverse invertebrate communities, where there are also multiple species with the same function (functional redundancy), mitigating the effects of climate change related species loss on ecosystem processes.[11] Dead wood accumulation sequesters more carbon and boosts carbon storage in soils, supports flood mitigation by slowing water flows and increases water infiltration and absorption.[8]



## *Existing woodlands*

### Drivers of structural complexity

Sustainable management in existing woodlands maintains structural complexity, higher biodiversity and overall favourable condition alongside supporting greater resilience and multifunctionality.[8, 12, 13, 14] Actions include reducing pressures (pests, diseases, deer grazing), promoting natural regeneration, accepting a greater mix of tree species, encouraging continuous cover forestry (where relevant) and increasing decaying wood accumulation.[2] These actions also support a system's ability to adapt by improving its overall health and creating climate refugia.

Woodland age (including time since the start of restoration) and size also drive structural complexity.[6] Older woodlands have had time to develop a complex ecosystem with veteran trees, dead wood and a varied understorey to support more species. Larger woodlands have the space to support more habitats and niches which provide shelter and resources for genetically diverse species populations.[8] Structural complexity indirectly supports adaptive capacity as greater species and genetic diversity means there may be species present that are tolerant to different pressures and which may share functional roles, potentially compensating for species loss.[15]

### Best practice for woodland management

Although research has recognised that species targets may not be useful under changing environmental conditions therefore a new paradigm in nature conservation and ecological recovery is required, traditional management techniques often benefit structural complexity.

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## *Traditional management techniques*

Techniques such as coppicing and pollarding, are supported by best practice guidance.[16] Rotational coppicing in upland oak and wet woodlands increases tree age diversity and reduces shading, which encourages natural regeneration in non-drought prone areas.[2] Selective thinning and reducing tree density creates canopy gaps and open areas, supporting natural regeneration and the generation of microsites or niches.[5, 17]

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## *Deer management*

Reducing deer numbers or discouraging deer reduces woodland damage and supports structural complexity.[18, 19] In parts of the UK where deer populations are large trampling and browsing damages trees, inhibits natural regeneration, and reduces the diversity of ground flora, negatively affecting woodland structure, biodiversity, complexity and resilience. Advice regarding deer management is provided by the Forestry Commission and Defra.[20, 21]

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## Dead wood, and ancient and veteran trees

Fallen decaying wood and dead standing trees and branches support nutrient cycling, provide microhabitats for fungi and invertebrates and add to a woodland's structural complexity and biodiversity.[22, 23] These features provide shelter and specialised habitats for vulnerable species, promoting climate change adaptation and resilience.[2] The Forestry Commission provides guidance on dead wood management.[24]

Ancient and veteran trees provide structural interest, microhabitats and bird nesting sites in hollows and cavities, and maintain ecological processes and biodiversity but need protection from shading and soil disturbance.[22, 25] In younger woodland, veteranisation (where younger trees are intentionally damaged by creating holes or ring barking) can boost structural complexity by accelerating the formation of older tree-associated habitats.[26]

## Open areas and transitions

Open areas and rides provide sites for ground-nesting birds and allow sunlight to reach the woodland floor. This provides conditions for plants which support insects that cross-pollinate other plants and support insectivorous birds.[8, 27] They can contain other priority habitats and associated species, boosting biodiversity.[28] Soft edges act as transitional zones or buffers between woodlands and other habitats or land uses such as agriculture and are valuable areas of habitat for specialised species. They provide similar benefits to open areas and support ecological function and resilience.[29]

## Ash dieback

Ash dieback affects woodland health and is changing the structure and composition of mixed ash woodland.[2] Ash dieback creates gaps in the canopy and alters ground flora community composition which can benefit some native species and boost structural complexity.[30] However, ash loss negatively affects associated species and their functions.[8] How ash dieback affects complexity is context dependent but planting other tree species can boost biodiversity, structural complexity and slow the disease's progress by reducing sources of infection while increasing resilience.[31]

## Natural regeneration

Natural regeneration is assisted by reduced herbivory pressure which increases sapling survivability. Having a local source of seeds from plants adapted to local conditions also drives natural regeneration and conserves genetic complexity, enhancing woodland resilience.[32, 33] Evidence suggests that natural regeneration leads to more biodiverse and structurally complex woodlands although trajectories can be unpredictable and the process is slow.[32]



## *New woodlands*

### Challenges around structural complexity

New woodlands containing trees of uniform age, size and density are low in structural complexity, although this can be managed as they develop (see best practice above). Some newly created woodlands are also poorly connected to other patches which can reduce colonisation events from potential plant and animal species.[5] Woodland created on former industrial sites can also struggle to develop structural complexity.[6] Woodland Trust guidance addresses the challenges around woodland creation and complexity.[34]

### Natural colonisation vs tree planting

Woodland creation strategies can include natural regeneration and tree planting which have different benefits and challenges. Natural colonisation can lead to locally adapted and resilient woodlands with greater structural diversity. It also minimises risks from introducing pathogens from infected trees.[35] Outcomes can be variable and woodland establishment is a slower process, while there are knowledge gaps over how to start, target and manage natural colonisation.[32] Combining planting and natural colonisation can help reduce the uncertainty associated with natural processes, and can produce complex woodlands with greater stem density and canopy cover, greater vertical complexity, more biomass, and provide opportunities to add desired species.[36]

### Driving and supporting structural complexity

Reducing herbivory pressure and ensuring there are local seed sources support natural regeneration by increasing the likelihood of seed establishment and survival.[32] Transitional areas at the edge of woodlands support complexity, whilst interventions during the establishment phase to introduce complexity features include selective thinning, veteranisation, accumulating dead wood, creating log piles and ring barking.[34]

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## *Landscape level considerations for structural complexity*

### Connectivity

UK woodlands tend be small, isolated and are affected by habitat fragmentation and biodiversity decline.[12, 37, 38] Landscape connectivity allows migrating or mobile species, such as moths, to move between habitat patches, supporting diversity and abundances, with new woodlands acting as stepping stones.[8] Moth species also respond positively to structural complexity.[39] Habitat proximity can lead to colonisation by species from other habitat types which can also be seen in highly functional older woodlands, indicating that species identity is not always tied to functionality, but that complexity and overall diversity is.[5, 6]

### Site size

Woodland expansion boosts biodiversity in old and new woodlands. Larger woodlands can support more species, microhabitats and bigger, genetically diverse populations, which improves adaptive capacity.[5, 15] Creating new woodlands adjacent to existing ones also aids colonisation and can enhance structural complexity by creating younger areas of woodland next to mature trees.[8]

### Habitat heterogeneity

Larger mixed sites where woodlands are accompanied by other habitats, are structurally complex, supporting different suites of species with higher species and functional diversity. Habitat variety creates variation in environmental conditions and microclimates that can buffer species against the risk of extinction or decline under climate change.[40] Habitat mosaics allow multiple ecological communities to form, supporting landscape-wide diversity.

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## Network complexity

The diversity of interspecies interactions, or network complexity, depends on the number of potential interactions observed, whether specialists interact with similar plant species as generalists and how many plant species each insect interacts with. These metrics can also indicate how connected, stable and resilient the network is under changing conditions.[41, 42] Insect feeding behaviour and outputs, contributes accessible forms of plant nutrients, such as nitrogen and phosphorus, to a woodland's nutrient cycle, stimulates compensatory growth and boosts plant productivity.[43, 44, 45] Plant-herbivory interactions and networks support higher abundances of decomposers such as earthworms and arthropods and contribute to long-term ecosystem stability.[46]

### *Network complexity drivers and modifiers in woodlands*

Woodlands that are older, larger and close to other woodland habitats are more likely to have more complex networks and can be more structurally complex. Age and size are linked to network robustness and stability on individual sites and across multiple sites. Older sites have been exposed to more opportunities for colonisation by insects and other taxa and support features that can take a long time to develop, for example rot holes, cracks and crevices.[42]

In older and larger sites, there can be localised areas of high resource density, supporting less mobile woodland species and breeding populations. Shifts in plant and invertebrate community composition in intermediate aged woodlands, away from early successional species, means network complexity may not be as high.[42]

Network complexity is also higher in woodlands which are within 1km of other woodlands, with more interspecies connections, greater resilience and stability. The presence of other habitat patches helps invertebrate movement and colonisation of new woodland patches.[42]

Structural and invertebrate complexity combined can indirectly affect plant–herbivore dynamics, whilst vegetation heterogeneity and variation in tree size boosts insect and plant diversity and provides opportunities for invertebrate specialisation.[5, 6, 47] With greater invertebrate complexity, interactions can become more specialised (each herbivore interacts with fewer plant species) potentially increasing species evenness, reducing overall herbivory pressure and in turn supporting plant functional diversity.[4, 6]

## Grasslands

Semi-natural grasslands cover around 10% of the UK's land area. Ecosystem services provided by grasslands include carbon sequestration, climate regulation, clean water, flood protection and pollination, in addition to cultural and aesthetic value.[2, 48] They prevent sedimentation and soil erosion into rivers, slow down water flow to reduce flooding, provide food and habitat for pollinators, and store carbon via plants and soil.[49, 50] Species-rich grasslands are priority habitats and support more than 1,400 species of insect, including invertebrates that feed on roots, stems and leaves.[51, 52] Pollination maintains invertebrate and plant communities and supports food production.

Biodiversity and plant richness is strongly linked to the ecosystem services provided by semi-natural grasslands.[53] Research from RestREco shows that resilient and multifunctional grasslands are strongly tied to high plant diversity/complexity, and structural and network complexity.

### *Plant community complexity*

Species-rich grasslands have diverse plant and animal communities, including some specialised species. They provide high concentrations of nectar and pollen for pollinators, other food sources and habitat to support richer herbivore communities.[49, 54]

More diverse grasslands have higher resilience through more efficient resource and energy use, productivity and resource diversity.[47] They contain plant species that are more likely to survive or recover from disturbance or persist under dramatic change and have greater functional complexity and redundancy, which maintains overall multifunctionality if species are lost.

## *Drivers of plant complexity and management*

Prioritising plant diversity in grassland restoration and management can support overall complexity and grassland health. Grassland regeneration on former agricultural sites is quicker and leads to more complex plant communities when areas are restored using brush harvested seed or hay containing seeds taken from existing species-rich grasslands or seeded with species-rich seed mixes.[6, 52, 55]

Livestock grazing can boost plant diversity by limiting plant succession where vigorous grasses dominate and suppress smaller plants, ultimately leading to a decline in nature conservation value.[53, 56] Grazers also trample seeds into the ground and create microhabitats for seedling regeneration and coexistence of more plants.[52, 57, 58] Low intensity grazing encourages summer flowering, supports invertebrate and fungal diversity and is associated with resilience and adaptation, particularly in calcareous grasslands.[2, 59, 60]

## *Species identity and habitat proximity in relation to complexity*

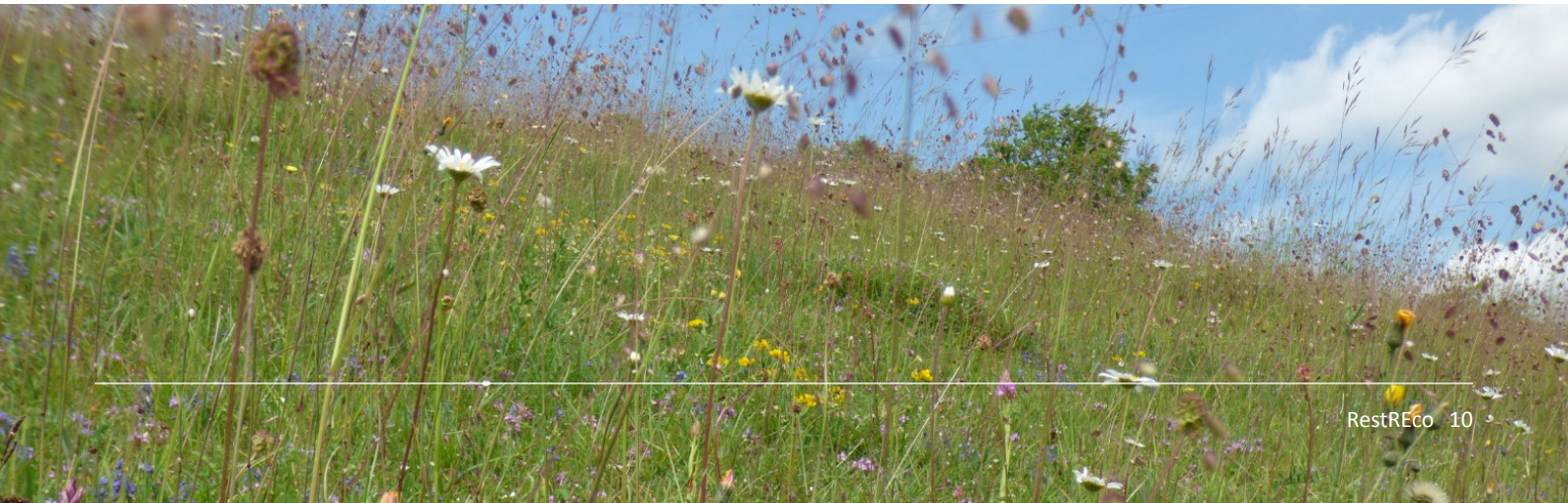
Research from RestREco has identified that plant complexity may not necessarily be tied to the identity of the species within the plant community i.e. it does not simply mirror historical refence communities. There is also evidence that the proximity of other grasslands does not always result in a more complex community of grassland plants.[6] Grassland plant complexity can be supported by limited cross habitat colonisation, where plants from another habitat type can be found within a site containing a different habitat (e.g. woodland plants in grasslands).[61] These non-grassland species can also contribute to functional diversity, redundancy and resilience. Climate change driven shifts in community composition in grasslands or the establishment of scrub in drought prone sites, which provides shade and microrefugia, can be beneficial.[2]

# Structural complexity

Structural complexity in grasslands includes variations in sward height, plant cover, the presence of flower heads and grasses, bare ground, scrub and clumping of vegetation.[59] This variation supports multifunctionality by providing different conditions to support animal species from different functional groups. A mixture of short turf, patches of bare ground and clumps of taller grass and some scrub allow wildflowers and smaller plants to thrive without being swamped, provide spaces to support different insect behaviours, and provide cover for other invertebrates. Bare ground also provides germination niches for plants.[58]

Structural complexity supports more invertebrates, richer invertebrate communities and functional richness.[6] Niches or microclimates in bare ground, shade under scrub and vegetation clumps can be exploited by different species and permits species coexistence and persistence and, alongside variation in topography, provides climate refugia, and breeding and hibernation sites.[47] Sward architectural complexity includes variation in vegetation heights and types (fine or tussocky grasses, legumes, ruderals) and distribution of shoots and roots. Sward complexity supports spiders, beetles, true bugs, predatory beetles and herbivorous true bugs and, alongside plant cover and flower diversity, supports pollinating, herbivorous, predatory and detritivorous invertebrates.[54, 62]

Guidance on grassland management, regeneration and creation from, for example Natural England and Defra, supports management for structural complexity and cutting and grazing practices.[58, 59, 63]



## Network complexity

Larger and older grassland sites have more complex plant–pollinator networks.[6, 42] Population sizes tend to be greater on larger sites, with more interactions and greater resilience to changes in environmental conditions or disturbance. For example, in a more connected network, species loss can be compensated for by another species with a similar function. Older sites have been exposed to more colonisation events by invertebrates and contain habitat features, such as specific host plant species or groupings, that take a long time to develop.[64] Increasing colonisation sees greater resource competition, more specialisation or invertebrates seeking new niches in a bid to avoid competing. This can result in novel interactions and further network complexity.

Other drivers of network complexity include structural variation in plant communities or localised structural complexity. Spatially complex clusters of plants provide more resources, reducing the need for energetically costly foraging. Presence of other grasslands in the wider landscape helps colonisation and functional redundancy and leads to stronger and more complex networks.[6, 42] Pollinating species found in grasslands are highly mobile, travelling long distances to forage and often breeding in other habitats.

Continued low-intensity grassland management is vital for a diverse and resilient interaction network – a lack of management can lead to reduced plant species richness and a loss of specialist pollinator species, reducing overall ecosystem function and pollinator diversity.[65]

Best practice promotes grassland size, supports older grassland sites, promotes a mix of short sward, resource-dense scrub and taller vegetation patches, and traditional management including appropriate livestock grazing regimes.

## Soil microbial complexity

Healthy and diverse soils are important to habitat function, providing ecosystem services such as nutrient cycling, biomass accumulation and carbon sequestration. Vital to soil biodiversity is the presence of diverse microbial communities (bacteria and fungi) which carry out these fundamental functions.

Initial research from RestREco has identified some drivers which affect the complexity or diversity of soil microbial communities in woodlands and grasslands. The starting context for a new woodland is important – former industrial sites tend to have higher soil microbial complexity (bacterial and fungal) compared to former agricultural sites, but this correlation is mediated by soil pH.[6] This could indicate that microbial communities on sites being restored from other land uses, such as agriculture could be supported through soil inoculations or translocations or planting vegetation with favourable associations with soil microbiota.[66]

In grasslands, grazing regimes can affect soil microbial complexity although this depends on grazing frequency and the type of livestock among other factors.[6, 82] Other research shows that high stocking densities can lead to soil compaction which can reduce the abundance of soil fauna.[53]

Research by RestREco on what drives soil microbial complexity is still being conducted with several papers currently in review.



## Measuring complexity

Evidence from the RestREco project shows that complexity cannot be captured by a single metric.[6]

A more holistic approach should combine multiple indicators of ecological complexity at both site and landscape scales. These could include measures of habitat structure and connectivity, species and functional diversity, food-web interactions, soil microbial communities and acoustic diversity. Emerging approaches such as environmental DNA, remote sensing and automated acoustic monitoring may help broaden the range of taxa and ecological characteristics that can be assessed.

Measures of complexity should be complemented by measures of ecosystem function and resilience. These might include indicators such as nutrient cycling, decomposition, carbon storage, pollination and predation, as well as the capacity of these functions to persist or recover following environmental pressures such as drought.

## Adaptive management

The aim of adaptive management is to provide a potential portfolio of actions and decisions – using a combination of indicators to assess progress and inform adjustments – that can be taken to ensure an ecosystem persists into the future or heads towards a predefined management target.

Principles of adaptive management:

- **accept uncertainty as a characteristic of ecosystem change and management outcomes;**
- **remain flexible and ready to respond to new evidence, evolving ecological conditions and changes in objectives;**
- **look beyond 'resistance at all costs';**
- **monitor consistently and use the data to inform future action and reduce uncertainty.**

## Applying adaptive management

Resist-Accept-Direct (RAD) is a decision-making framework that sets out three approaches to manage an ecosystem undergoing transformation and is compatible with adaptive management principles. Where frameworks, such as RAD, are being used, understanding the site, its threats and consistent monitoring are key.

A structured framework (Figure 1) can help practitioners and stakeholders work together to identify system changes, the acceptability of those changes, and develop a portfolio of actions under resist, accept and direct in response to environmental change. Monitoring is used to inform future actions and objectives.

Available resources to help identify threats and determine the vulnerability of individual features include the Natural England Climate Adaptation Manual, National Character Area profiles, Living with Environmental Change (LWEC) report cards and observations from colleagues or other partners.

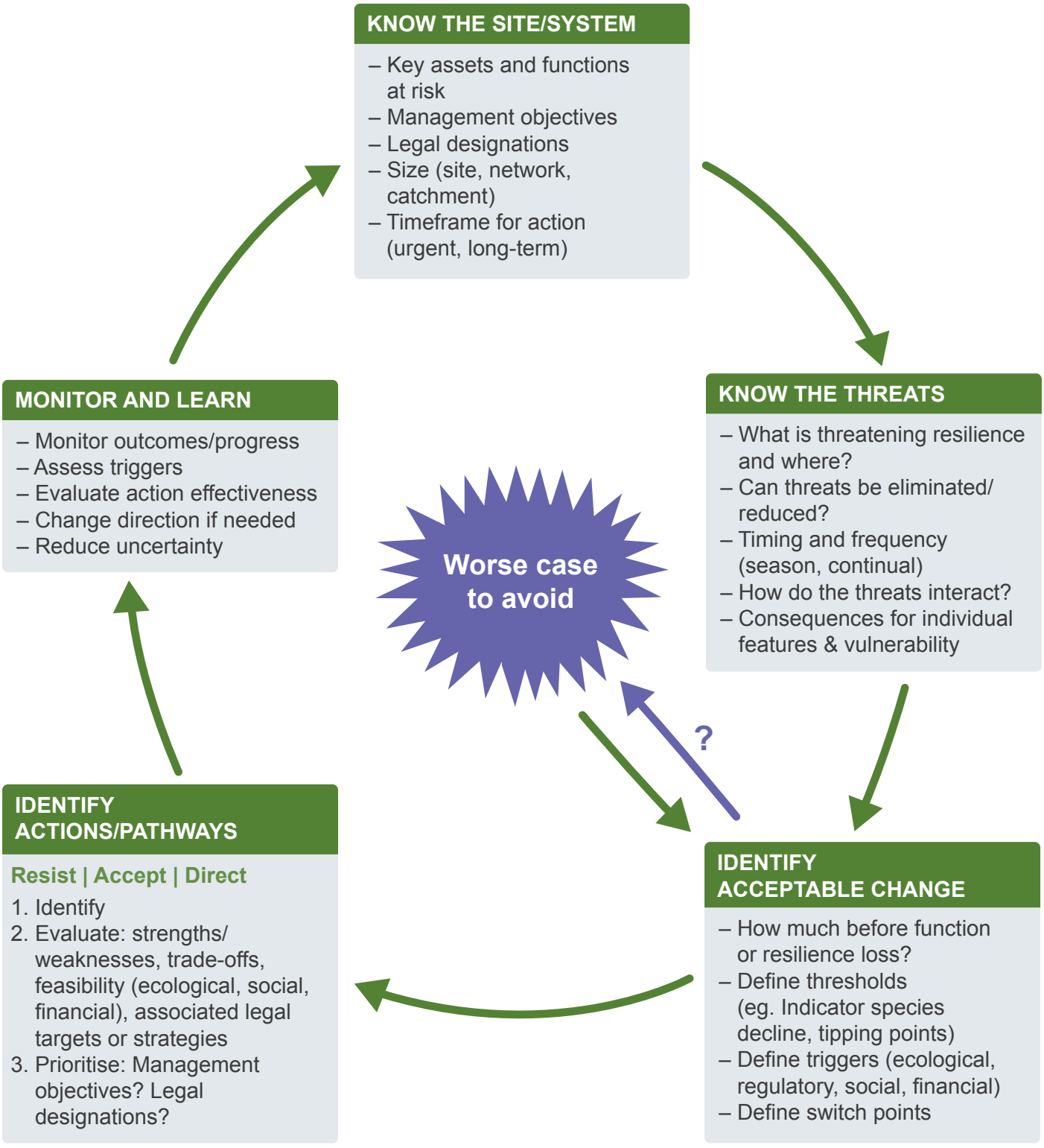



**Figure 1:** The decision-making process for adaptive management and resilience planning.

Triggers are feature or system indicators that suggest a system is in an undesirable state and spur pathway re-evaluation when they hit specific criteria. Switch points are points along an ecological trajectory when a choice is made to pursue a new RAD pathway. Identifying the worst-case scenario that practitioners want to avoid can help when there is uncertainty over how much change is acceptable.

The pathway identification stage identifies actions that support resilience and complexity under environmental change.

### *Monitoring*

Monitoring informs the rest of the process. It supports the identification of threats and triggers, increases system understanding and reduces uncertainty.

Monitoring can incorporate already established protocols such as species abundances for pollinators, birds, butterflies, bats and plants, alongside other metrics, such as signs of ecosystem degradation (changes in invasive species populations, pests/diseases), or changes in structural (volume of dead wood, amount of open space, variation in sward height), species (alpha diversity, number of native species) or network (number of interactions, number of plants fed on) complexity. Individual monitoring activities can be linked to specific threats and potential actions.[67] Monitoring includes scheduled formal reviews and informal observations.[68]

## Triggers and when to switch between RAD pathways

Combinations of RAD strategies may be needed as ecological change happens on multiple spatial and temporal scales. Having different approaches implemented in different areas, experimental manipulation or running pilot studies makes it easier to assess the costs, benefits and feasibility of competing options.

Pathway choice or switching can be challenging where environmental changes are erratic, ecosystem responses are uncertain or when there is movement towards an ecosystem with novel structure, function and species assemblages. A set of guidelines based on RAD in the field (Figure 2) can help.

### RESIST

Resisting change can be a short-term or temporary option if actions to resist meet the criteria (Figure 2), but in the long term may not be enough to maintain ecosystem function, habitats and biodiversity into the future.[69, 70]

Some pressures (e.g. herbivore damage, invasive species, nutrient pollution) can be managed to improve site condition, avoid tipping points, support species under climate stress and boost resilience to drought and flooding.[2, 69, 71]

Potential actions include restoring ecosystem hydrology, creation of climate refugia, maintaining topographic and vegetation structures and relocating rare or vulnerable species if their existing habitat is undergoing environmental change.[2, 72]

Traps to be aware of are inaction resulting from uncertainty or wanting to avoid scrutiny, sunk cost fallacy, and loss aversion.[70, 73]

#### Examples of resistance

Eutrophication, drought, sedimentation, saline ingress and species decline in the designated Special Area of Conservation at Bosherston Lakes in Wales, is being addressed through catchment management. Objectives include reducing nutrient runoff, improving water quality (short-term) and a managed transition to brackish conditions under sea-level rises (long-term).[74]

Pine martens (*Martes martes*) have been reintroduced to some UK forests to control grey squirrels (*Sciurus carolinensis*), reducing pressure on declining red squirrel (*Sciurus vulgaris*) populations.[75] Beavers (*Castor fiber*) have been reintroduced in areas to resist the degradation of wetlands and water quality in rivers, while slowing water flows and reducing flooding.[76]

## ACCEPT

Accepting allows the uncontrollable processes that are driving change to transform an ecosystem instead of trying to maintain historic conditions. It can be the next stage in system management when resistance is impractical (Figure 2).[68, 70] Actions can include managing for public safety, minimising the impact of other controllable pressures and improving connectivity for migrating species.[2, 77]

A new state may include novel species assemblages suited to changing conditions.[69] Challenges can include gaining social acceptance in areas with 'cultural landscapes' which can be addressed through public education.[77]

### Examples of accept

Acceptance includes allowing shifts in community composition as species ranges change while retaining function.[69, 78]

The Suffolk Local Nature Recovery Strategy has accepted the inland migration of saltmarsh and managed realignment in response to natural coastline erosion at the Suffolk and Essex Coast and Heath instead of building further sea defences to resist change.[79]

## DIRECT

Land managers can take deliberate action to steer a system towards a new state which is biodiverse and highly functional by working with ecological processes.[77] Although this approach can be more expensive and labour intensive than resisting or accepting initially, over time it could be more economical.[73] Directing leans on deep ecological and technical knowledge and some confidence that the resulting ecosystem will be viable, complex and functional.[70]

A system exceeds its adaptive capacity when change reduces biodiversity, hits ecological thresholds or tipping points (nutrients reaching unacceptable levels, increase in flooding duration or frequency), or lowers ecosystem health, function and resilience.[70, 71] Directing can be a response to a system diverging from management objectives for example changing to a less diverse habitat type in response to changes in fire frequency and intensity.[68]

Desirable ecosystem trajectories include the addition or enhancement of ecosystem services such as carbon sequestration, formation of regionally or globally vulnerable vegetation communities or habitats such as wetlands, new features supporting climate mitigation and species translocations.[73, 80] Novel ecosystems which are resilient and highly functional can emerge from climate-related changes in species dispersal patterns.[81]

Challenges can include actions only meeting one or two feasibility criteria, societal or legislative constraints or a current lack of funding.

### Examples of direct approach

Examples include the introduction of ecosystem engineers such as beavers to create wetlands, and bison to convert declining woodlands into grasslands.[78] Rewilding – ecological restoration geared towards reinstating natural processes and potentially missing species – is also an example of a direct approach.[77]



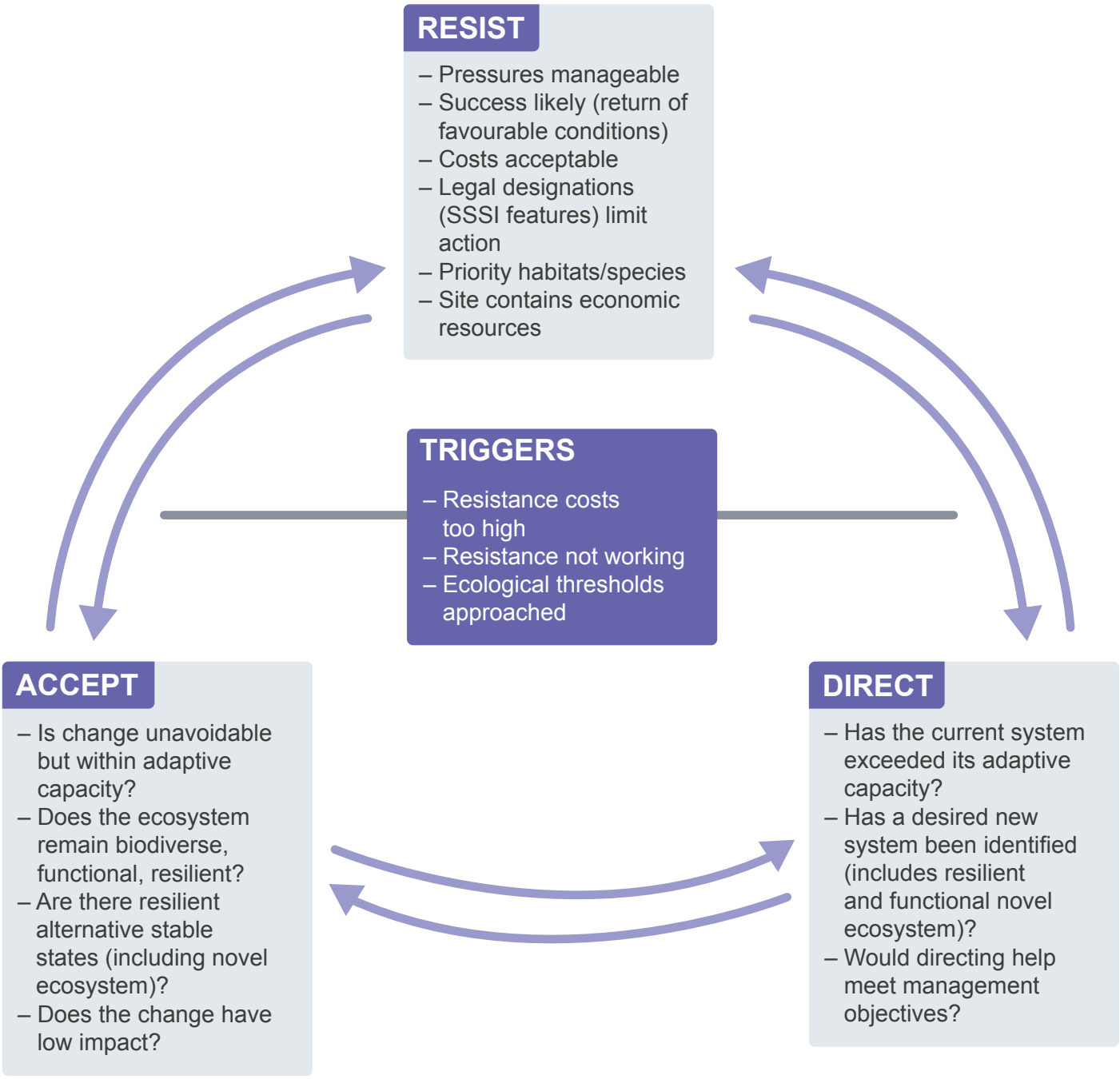



**Figure 2:** Framework showing the situations in which a practitioner might choose actions under the resist, accept and direct approaches.

# Conclusions

Restoration efforts to date have largely focused on targeting the restoration of ecosystems to a pre-disturbance, historic reference state; however, climate change and ongoing biodiversity loss creates challenges for nature restoration underpinned by such aims. The findings of the RestREco partnership project support the reconsideration of traditional aims for ecosystem restoration and nature recovery, focusing on complexity and resilience as a measure of success.

For UK woodland habitats, structural complexity (including species richness; variation in tree size and density; areas of open space; niches and microclimates; and deadwood and veteran trees) and network complexity (including herbivory, pollination, predation and mutualism) have been identified as important for function and resilience.

Research into grassland habitats in the UK have identified plant community complexity (species-richness), not necessarily tied to the identity of the species within the plant community; structural complexity (including sward height, plant cover, bare ground, flower heads, grasses, scrub and clumping); and network complexity, as important for function and resilience.

Drivers of complexity in woodlands and grasslands include management, age, size, heterogeneity, connectivity and establishment methods.

Initial research from RestREco has identified some drivers of soil complexity and microbial diversity but research is continuing.

Complexity should be measured through analysis of a range of indicators at different spatial scales complemented by measures of ecosystem function and resilience, with a flexible approach to management where actions are adjusted over time based on monitoring and changes in environmental conditions.





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# Glossary

| Term | Definition |
|---|---|
| **Adaptive capacity** | The ability of ecosystems, species and populations to adjust to environmental change and still maintain function. |
| **Adaptive management** | A flexible approach to managing ecosystems where actions are adjusted over time based on monitoring and changes in environmental conditions. |
| **Ash dieback** | A fungal disease that affects ash trees, causing leaf loss, crown dieback and potentially tree death. |
| **Biomass** | The total mass of living biological material within a given area or ecosystem. |
| **Components** | The individual elements or parts that make up a system. |
| **Connections** | Interactions, or energy and material flows within a site or landscape. |
| **Ecological complexity** | The number of components in a system and the number of connections among them. |
| **Ecological function** | Biological, physical and chemical processes that drive the movement and transformation of energy and matter. |
| **Ecosystem** | A community of living organisms and the physical environment, functioning together. |
| **Ecosystem restoration** | The process of assisting a degraded, damaged or destroyed ecosystem to recover its biodiversity, structure and ecological functions. |
| **Ecosystem services** | The benefits that people obtain from ecosystems, such as food, clean water, pollination, climate regulation and recreation. |
| **Functional redundancy** | The presence of multiple species that perform similar ecological functions, meaning the loss of one species may have less impact on ecosystem functioning. |
| **Habitat heterogeneity** | A variety of habitats and microclimates within an area, providing diverse conditions for different species. |
| **Historic reference state** | A set of historic environmental conditions and a specific suite of species present in an ecosystem at a particular point in time. |
| **Loss aversion** | Prioritising the avoidance of losses over achieving equivalent gains, which can lead to reluctance to change or stop a management approach. |
| **Natural Environment Research Council (NERC)** | A UK research council that funds and supports research into the natural environment. |
| **Natural regeneration** | Where habitats re-establish through natural seed dispersal, germination and colonisation, without deliberate planting. |
| **Network complexity** | The diversity of between-species interactions within a habitat or ecosystem. |
| **Novel ecosystems** | New species combinations interacting with a different set of environmental conditions. |
| **Phylogenetically** | Relating to the evolutionary history and relationships between organisms. |

| Term | Definition |
|---|---|
| **Resilience** | A system's ability to recover from or withstand disturbance without a loss of function or falling into a degraded or undesirable state.<br><br>A system's ability to resist, recover, adapt or transform to a robust state. |
| **Resist-Accept-Direct (RAD)** | An adaptive management framework that sets out three approaches to manage an ecosystem undergoing transformation. |
| **Restoring Resilient Ecosystems (RestREco)** | A project focused on understanding and supporting the restoration of resilient ecosystems. |
| **Soundscape complexity** | The existence of multiple biotic sounds, distributed unevenly, across a range of frequencies over time. |
| **Structural complexity** | Variations in the physical arrangement of an ecosystem horizontally and vertically. |
| **Sunk cost fallacy** | Continuing to invest in a management approach because of resources already spent, rather than considering whether it remains the best option based on current evidence and future outcomes. |
| **Tipping points** | Critical thresholds where a change or disturbance can cause an ecosystem to shift into a different state that may be difficult to reverse. |
| **Veteranisation** | Where younger trees are intentionally damaged by creating holes or ring barking to provide habitats for wildlife and support biodiversity. |





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RestREco

