RestREco

Policy briefing

Why ecological complexity matters

Overview

– The consequences of climate change and unchecked biodiversity loss are recognised globally, with the 30by30 targets set by the Kunming-Montreal Global Biodiversity Framework providing a call to action for countries to restore and reverse ecosystem degradation.[1]

– At a national level in the UK, mechanisms to halt and reverse biodiversity loss and address climate challenges are currently implemented through policy and legislative requirements including the Habitats Regulations, the 25-Year Plan to Improve the Environment, biodiversity net gain for development, Local Nature Recovery Strategies and protected sites.

– In the face of growing environmental pressures and shifting ecological baselines, ecosystem restoration to reverse ecological degradation is seen as a key solution.

– Despite restoration efforts to date, climate and ongoing environmental change makes returning sites to a historical reference state increasingly difficult in practice and inappropriate as a target.

– Targeting the restoration of past habitats and ecosystems without considering the resilience of that system to future environmental pressures, has the potential to undermine the effectiveness of nature recovery efforts in the long term.

– The Restoring Resilient Ecosystems (RestREco) partnership project set out to research the effectiveness of current aims, practices, policy and legislative approaches and contribute to the evidence base underpinning restoration efforts towards achieving ecological restoration that is functional and resilient in a changing world.

– Through research into UK woodland and grassland habitats, the project examined how complexity in ecosystems at different trophic levels could achieve the target of maintaining function and resilience through differing intervention approaches and the role of complexity to determine success.

– Structural, network and plant and insect complexity were identified as the most important components of complexity. Continued sustainable management including traditional techniques and low intensity grazing are among key drivers. Although complexity can be measured using existing metrics, it cannot be reduced to a simple indicator.

– The findings of this research add to our existing knowledge base, providing insights to inform policymakers and restoration practitioners, and support effective action and metrics.

Cranfield University · Forest Research · National Trust · UKRI Natural Environment Research Council · UKCEH · University of Stirling

1 Introduction

1.1 The case for ecosystem restoration

Society is reliant on a healthy and functioning planet, yet accelerating biodiversity loss and human-induced climate change are undermining the ecosystems and natural processes on which human wellbeing depends. The provision of food, water, clean air, climate regulation, soil formation, raw materials and opportunities for recreation and wellbeing are all threatened by the nature and climate crises. Reversing biodiversity and habitat loss and adapting to rapid climate change is arguably society's greatest challenge both now and in the years ahead.

Evidence from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlights the fundamental importance of biodiversity and ecosystem functioning to human wellbeing, as reflected in the UN Sustainable Development Goals (SDGs).[2] The Dasgupta Review further highlights the need to embed the value of nature and natural capital within economic decision-making to support the long-term sustainability of the planet.[3] The consequences of failing to do so are increasingly recognised, including the UK National Security Assessment, which identifies risks to national and political stability arising from ecosystem collapse, increased mortality from extreme weather events and disruption to food systems leading to increased hunger.[4]

Nature should also be conserved for its own intrinsic value. Species, ecosystems and ecological processes are a result of the Earth's evolutionary history. They are a unique part of our natural world and are irreplaceable. Conserving biodiversity maintains the richness and complexity of the living world into the future.

Latest climate projections show that all areas of the world are warming, with global surface temperatures between 2011 and 2020 reaching 1.1°C above those recorded between 1850 and 1900.[5] The UK is set to experience milder, wetter winters and hotter, drier summers with more intense and frequent extremes.[6] The impacts of this emergency are already being felt with Europe and the UK experiencing multiple, extended heatwaves that consistently establish new records for both temperature and drought. Threats such as wildfire and flooding are also increasing in severity and frequency across the globe.

In the face of accelerating environmental pressures and rapidly shifting ecological baselines, ecosystem restoration is identified as a key solution in the response to the twin issues of biodiversity loss and climate change, whilst contributing to national and regional priorities as defined by policy and legislation.

1.2 The restoration challenge

1.2.1 Ecosystem services

Natural processes underpin ecosystem function, which in turn provide ecosystem services that support human wellbeing and economic activity. These services are commonly grouped as provisioning, regulating, supporting and cultural, encompassing benefits such as food and water provision, climate regulation, nutrient cycling and opportunities for recreation.

Biodiversity is strongly tied to ecosystem function with more diverse systems producing, for example, more plant biomass, supporting a greater number of plant pollinators (more than 75% of the world's food crop types rely on animal pollination[2]) and being more resilient to shocks and disturbances.[3, 7] However, the ability of the Earth's systems to provide or support these functions is under threat from the nature and climate crises.

Biodiversity loss through the degradation and loss of habitats weakens the ability of ecosystems to contribute to climate mitigation and adaptation, threatening ecosystem resilience under pressure. At the same time climate change drives biodiversity loss through impacting species populations, causing habitat shifts and changes to species' distribution patterns with many species unable to adapt or shift their ranges quickly enough in response.[8, 9]

All this is against a backdrop of approaching environmental tipping points and thresholds, which, if crossed, could plunge the world into an irreversible trajectory. Some of these tipping points may have already been crossed – many of our coral reefs, for example, are already suffering from dieback – and will be accompanied by continuing losses in biodiversity.[2]

The drastic consequences of ignoring the nature and climate crises means we cannot continue with 'business as usual'. Despite committed conservation efforts, anthropogenic-driven biodiversity loss continues apace, and while the use of renewable energy has increased dramatically over the past decade, greenhouse gas emissions continue to rise in tandem with high temperatures and the frequency of extreme weather events.[9, 10, 11, 12] To tackle these linked crises, we need a new way of thinking, new methods of working and strong commitment to drive the changes we need to make to secure the future of the planet.

1.2.2 Meeting our commitments

The consequences of runaway climate change and biodiversity loss have been recognised globally. As a result, there are multiple global pledges and programmes to promote nature and conservation and address climate change, which the UK has signed up to. These include the 30by30 Kunming-Montreal Global Biodiversity Framework, committing the UK to protect 30% of its land and seas for nature and to restore 30% of all degraded ecosystems by 2030; UN SDGs 13 (climate action), 14 (life below water) and 15 (life on land); the Ramsar Convention on Wetlands to conserve wetlands of international importance; and the Leaders' Pledge for Nature.

The UK is a long way from meeting its 30by30 protection target. It is estimated that just under 6% of land in the UK is effectively managed for nature and although 38% of seas are designated as Marine Protected Areas, up to date monitoring data is lacking. In England, only 2.83% of land meets the criteria, 2.4% in Wales, 12.63% in Scotland and 4% in Northern Ireland.[13] For the restoration target, progress has been made but at an insufficient rate.[14]

The UK's progress towards the UN's SDGs is also poor with challenges or significant challenges remaining for most goals.[15]

1.3 A new approach – reconsidering the aims of restoration

Climate change is irreversibly changing species distribution patterns and abundances, habitat structure and water availability on a landscape scale. In light of these changes, nature recovery will face new challenges in attempts to slow or halt the biodiversity crisis. The stability of ecosystem services and biodiversity continues to decline with many of the UK's habitats reported to be in poor condition despite committed efforts from land managers and practitioners to conserve and restore both habitats and species.

Restoration efforts to date have largely focused on targeting the restoration of ecosystems to a pre-disturbance, historical state using varying degrees of intervention to repair or restore habitat degradation and destruction, including targets for species.

The four-year Restoring Resilient Ecosystems (RestREco) partnership project, funded by the Natural Environment Research Council (NERC), set out to reconsider the aims of ecosystem restoration. Focusing on UK woodland and grassland habitats, the project examined complexity and resilience as an aim in relation to nature recovery rather than the re-creation of a specific target ecological community.

This document reports the findings of the RestREco project, contributing to the existing evidence base to support policymakers, land and conservation practitioners. It aims to assist those not already managing for complexity while providing additional insight for those that are, to determine effective action and measures of success in relation to ecosystem restoration best practice.

2 Resilience, complexity and a new paradigm

2.1 Approaches towards conservation and historical reference states

Typically, nature conservation has focused on the maintenance or restoration of ecosystems to historical reference states, that is to a particular point in time based on historical environmental conditions and a specific suite of species. This approach continues to shape many 21st-century laws and policies for nature conservation and recovery.

Permanent and accelerating environmental change challenges traditional approaches to nature conservation. Increased understanding of the drivers and ongoing pressures of environmental change, particularly climate change, suggests that historical conditions may no longer provide an appropriate basis for conservation. Changing climatic conditions are shifting species ranges and distributions, whilst altering the environmental baselines against which conservation outcomes are assessed. This makes it increasingly difficult to define or maintain fixed species assemblages and historical ecosystem states.

There is also uncertainty when predicting how climate change will affect ecosystem structure and function, and species assemblages. Changes are likely to be non-linear and rapid and using historical conditions to predict future states is unlikely to be useful.[16] Traditional conservation methods may not necessarily lead to more resilient systems or systems that are able to support or maintain ecological processes and organism diversity.[17] There is a need for a greater understanding of climate change and how it interacts with other drivers of biodiversity loss, plus a willingness to accept uncertainty and to adopt an open and flexible approach to conservation.

2.2 Ecosystem functions

Ecosystem functions are what keep ecosystems self-sustaining and productive. They comprise of biological, physical and chemical processes that drive the movement and transformation of energy and matter. Functions include the pollination of plants, the locking away of carbon in the soil, the decomposition of organic matter to release nutrients back into the environment, and primary productivity, which is the production of biomass or organic matter that is available to be consumed (Figure 1). These functions also maintain global ecosystem processes such as the water cycle, which we rely on heavily.

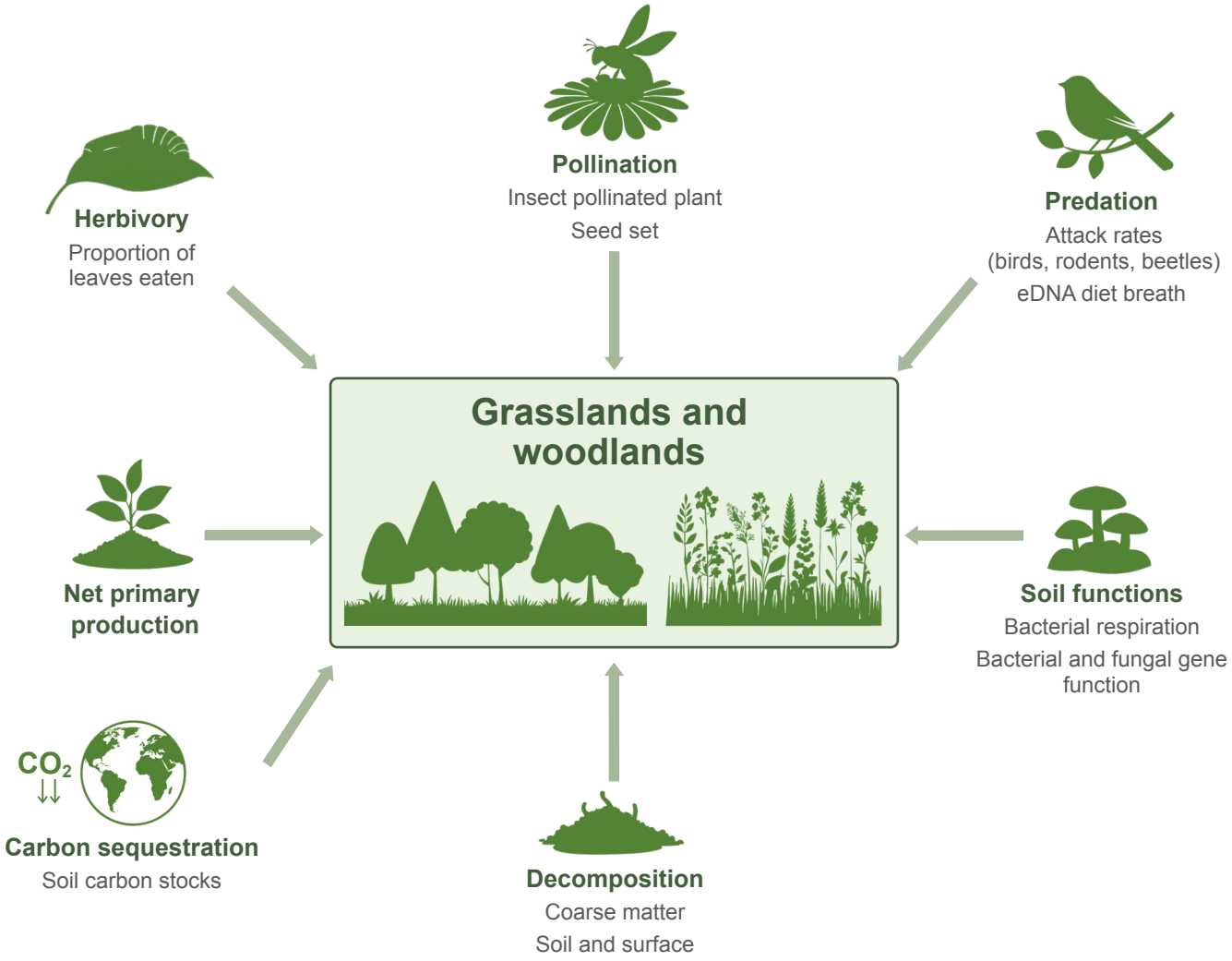


Figure 1: A graphical representation of some of the functions and processes that occur in ecosystems. Processes pictured were among those measured by RestREco research.

Ecosystem functions are provided by all the living things in an ecosystem, from soil bacteria and fungi to larger herbivores and predators, and their interaction with ecosystem properties such as climate, geography and soil. This is because plant and animal species have specific functional traits, that is they have particular ecological roles/functions (effect traits) and ways of responding to environmental conditions (response traits). These traits shape the ecosystem processes that underlie these functions and there is evidence that ecosystem functions are largely driven by species functional characteristics.[18] A diverse community of species is important to ensure the range of processes that drive ecosystem structure, energy transformation and renewal is maintained – i.e. that there is functional diversity.

At the same time, the positive relationship between biodiversity and functional diversity is often shown to plateau. At a certain point as biodiversity increases, the addition of more species results in the presence of multiple species with the same functions.[7, 18] This functional redundancy is also vital to maintain the processes that keep ecosystems alive – it ensures individual functions within the ecosystem are maintained should there be a loss of species.

In a world where nature, ecosystems and their functions are in decline under a changing climate, ecological restoration and nature recovery provides the means to address the issues identified in the previous sections. Restoration involves creating the habitats and environmental conditions to support a variety of plants and animals, which in turn secures the ecological processes that drive ecosystem function, while helping to mitigate climate change by restoring habitats such as grasslands, diversifying woodlands and improving soil health. However, it is important that restoration efforts result in ecosystems – and their functions – that are fit for future environmental conditions which are likely to be very different from current conditions.

2.3 Defining resilience

Previous understanding around resilience has largely focused on resistance or recovery.[19] However, as climate change is an ongoing pressure, current thinking has expanded the concept of resilience to include a system's adaptive capacity, the existence of multiple stable states for a particular set of environmental conditions and the idea of actively transforming a system into a new state that may have a greater resilience than historical systems.[20]

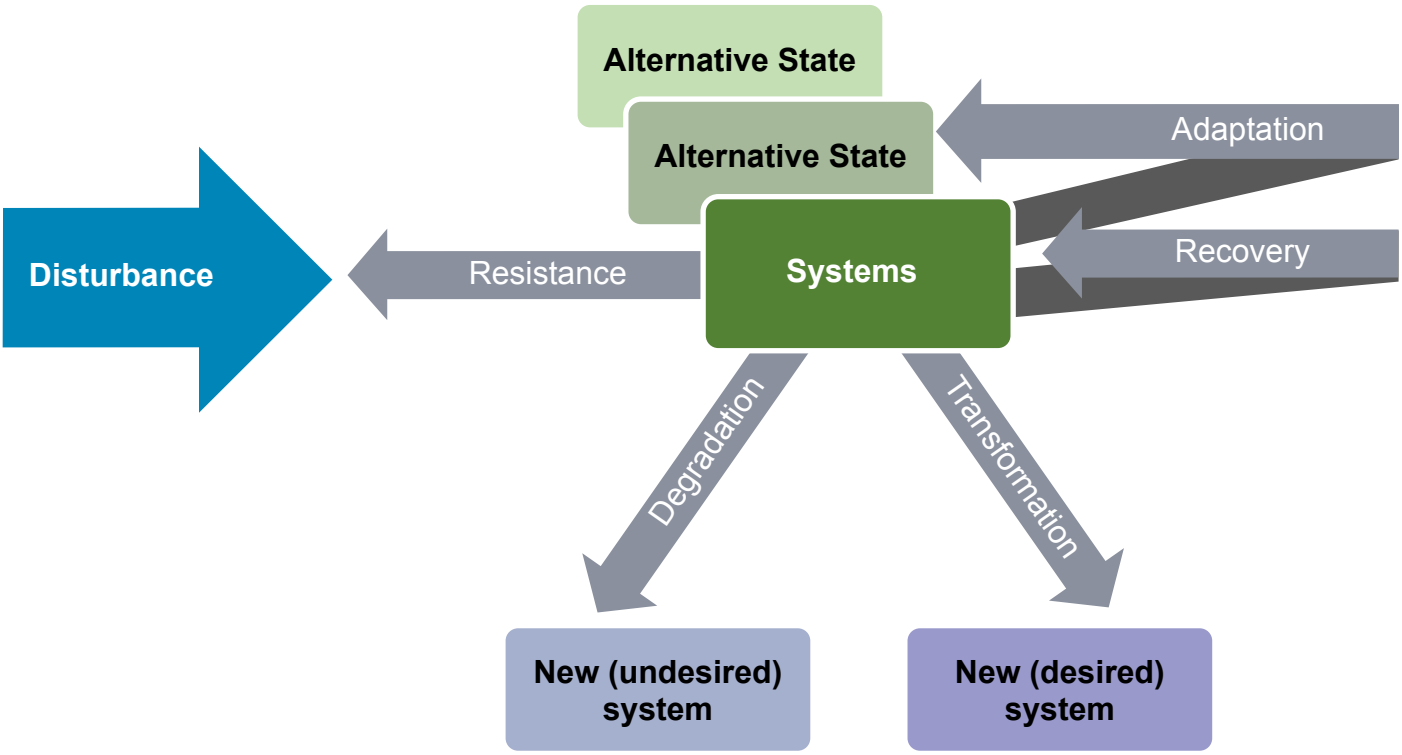


Figure 2: Conceptual model of ecological resilience, illustrating how ecosystems may respond to shock, threats, and stress by absorbing impacts and continuing to function (resistance), bouncing back (recovery), through adaptation without losing character or function, or transformation into a new system.[21]

2.3.1 Adaptive capacity

Adaptation can occur through genetic changes, species composition changes and range shifts, and changes in species behaviour, physiology and interactions[20]. Such adaptation allows the system, species or population to persist – it strengthens and builds resilience. The system, population or species 'evolves' to cope with future change or disturbances.

Under resilience theory, the disturbance can be persistent enough that the ecosystem transforms into a different system altogether, for example from a species rich grassland to bare soil, an alternative stable state. This transformation can also be guided by humans – the system is actively managed with transformation and future resilience in mind. There are adaptive management strategies that directly take this into account (see section 3.2).

Biodiversity is important for promoting adaptive capacity and resilience in an ecosystem. Having a variety of species means there will be species present that are tolerant to different pressures, ensuring that the community is not lost under that pressure. At the same time, if those species that respond differently to environmental change have similar functional roles, species can compensate for the decline in other species, reducing the risk of losing functions. This is known as an insurance effect.[20]

2.3.2 Drivers of resilience

Mechanisms which drive ecosystem or functional resilience occur at species, community and landscape level.

Species-level drivers of resilience include low sensitivity (greater tolerance) to environmental change, rapid rates of population growth (species' populations recover quickly after a disturbance), the ability to change behaviour or physiology to survive environmental change and greater genetic variability.

At a community level, ecosystems have greater resilience when species that are important for ecosystem functioning are not all vulnerable to the same environmental pressure. The existence of functional redundancy also supports resilience by providing insurance against loss of function. Functional resilience also relies on ecological networks such as pollination networks, predator–prey interactions and food webs. Networks containing multiple, well-connected species are more robust because the loss of a species is less likely to result in extinction cascades.[20]

Across a landscape, habitat heterogeneity, connectivity between areas and the presence of larger areas of natural or semi-natural habitat support resilience. Heterogenous landscapes can provide resources for different species, microclimatic refugia for more vulnerable species and support overall biodiversity. A well-connected network of sites facilitates species recolonisation following environmental disturbance, supporting population and ecosystem function recovery. Larger areas provide more and varying resources which supports higher species richness and larger population sizes. In turn, this supports greater functional redundancy and genetic diversity.

2.4 Introducing complexity

Ecological complexity is strongly associated with ecosystem resilience. Complex ecosystems typically contain greater biodiversity, more interactions between species, greater spatial and temporal variability and greater functional redundancy.[22]

The RestREco project proposes complexity (at multi-scales) as an aim when restoring ecosystems; this differs from the assumption that complexity will develop over time through targeting a particular reference state.

Complexity is defined pragmatically as "the number of components in a system and the number of connections among them".[23] Components include vegetation heights/height classes, species, trophic levels, insect biomass and ecotones. Connections can include species interactions such as mutualism and herbivory, feeding relationships and connectivity between habitat patches.

2.4.1 Complexity across spatial scales

The association between complexity and resilience is relevant at all levels of ecological organisation, from genes to ecosystems (Figure 3).

Complexity pyramid

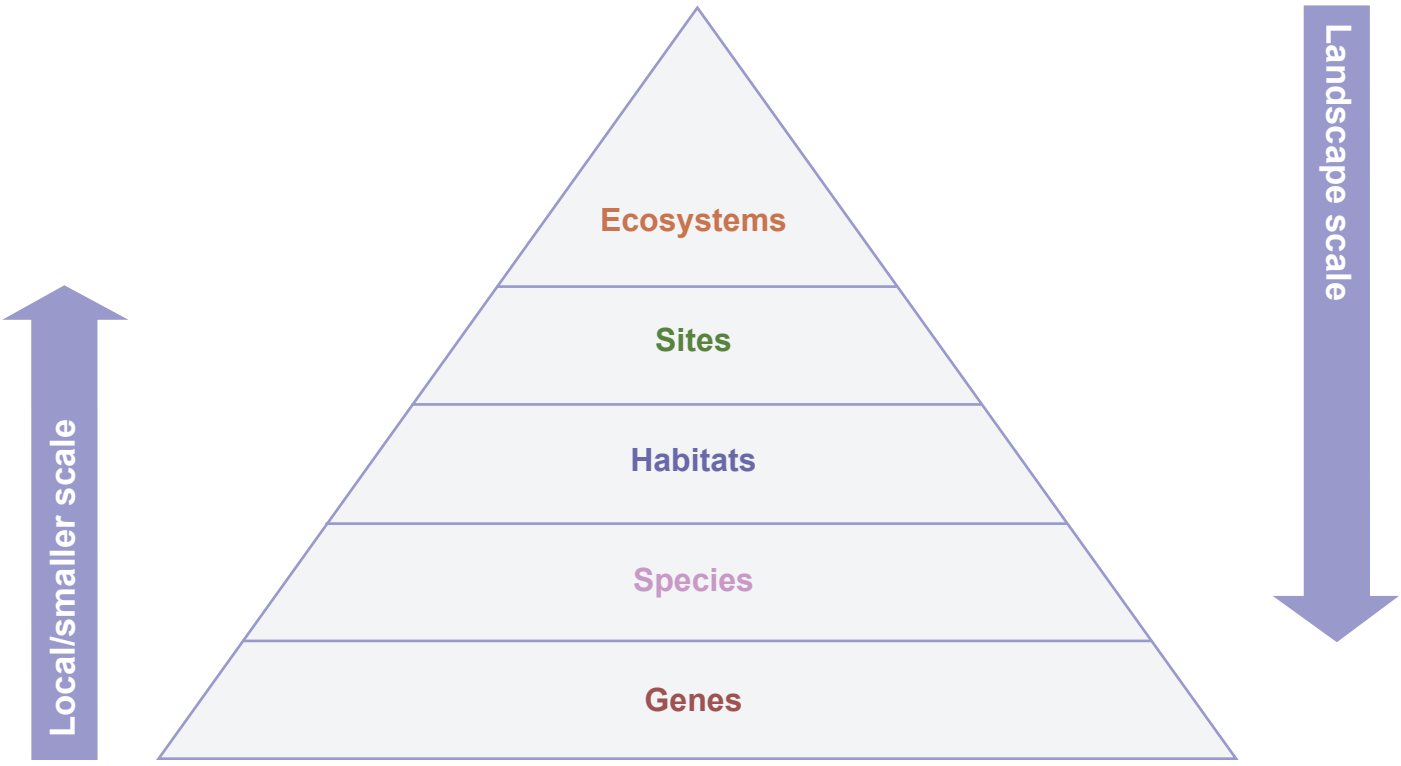


Figure 3: Complexity can be considered across all levels of ecological organisation, with genes at the lowest level and ecosystems at the top. Each level in the pyramid builds on the one below eg. Species complexity includes genetic complexity as well as its own complexity components (species richness, functional diversity, interactions).

At the genetic level, greater genetic diversity can increase a population's ability to adapt to environmental change. At the species level, complexity includes species richness, functional diversity and the variety of interactions between species. Habitat complexity includes species, functional and genetic diversity, as well as structural variation.

At the local and landscape levels, complexity is supported by diverse species, habitats, microclimates, niches and transitional areas (ecotones), which can provide refuges and help species move as conditions change. Landscape habitat mosaics and connectivity allows mobile species to migrate and maintain local functions. At the site level, complexity comes from multiple habitats, communities, species and functions. Ecosystem complexity brings these elements together, including their interactions and flows of energy and materials across the landscape.

Actions to promote complexity also depend on the spatial level. Species complexity can be supported through site-based actions while overall ecosystem or landscape complexity requires regional action or planning between multiple organisations. Landscape-scale planning can ensure there are a variety of habitats across an area or there are different sites to fulfil different roles including production, diversity and recreation.

2.4.2 Important components of complexity

Complexity is multi-dimensional. Different aspects of complexity develop independently of one another. For an ecosystem to be described as complex, multiple aspects must therefore be considered.

The evidence gathered so far from the RestREco project has identified structural complexity, network complexity and complexity/diversity of plants, insects and other species groups as important components of complexity and this is dependent on habitat type: not all habitats respond in the same way to different aspects of complexity. In addition, soil microbiome complexity has also been identified as an important component.

Structural complexity

Research undertaken by the RestREco project into woodland and grassland habitats has identified that key aspects of structural complexity include variation in tree/sward heights and ages; presence of areas of open space/variations in plant cover; the presence of niches and microclimates (such as dead wood and veteran trees); and the existence of multiple vegetation storeys.

There is evidence that structural complexity results in more diverse plant, bird and insect communities – and accompanying functional diversity and redundancy – which in turn leads to greater resilience.

Higher structural complexity is also directly linked to ecosystem services, such as supporting greater carbon sequestration and flood mitigation. Among the ecosystem services supported by structural variation in grasslands are pollination, flood prevention, erosion control and food for livestock.[24]

Plant community complexity

More diverse ecosystems are often more resilient to disturbance. Greater plant diversity is strongly associated with a more efficient use of resources and energy, higher productivity and resource diversity.[25] At the same time, diverse plant communities contain species that are more likely to survive disturbance or regrow once the disturbance has passed. Plant complexity is a major driver of structural complexity.

There is evidence that grasslands with greater plant diversity store more organic carbon in the soil and semi-natural grasslands are often a net sink for greenhouse gases.[26, 27] Grasslands that are species rich also have greater resilience to flooding, slowing down water flows and reducing runoff.[24]

RestREco research 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 to a grassland undergoing restoration does not always result in a more diverse community of grassland plants. For example, best practice recommends creating or restoring grasslands close to sites of the same habitat, but the research has shown that having a high percentage of grasslands within 2km of a site does not always affect levels of grassland plant complexity.[28] Plant complexity can be supported by a small amount of 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).[29] These non-grassland species can contribute to functional diversity, functional redundancy and resilience. There is also support from other sources for permitting changes in community composition in grasslands where this is driven by climate change and for allowing scrub to establish in drought prone sites.[30] This scrub can provide shade and microrefugia for invertebrates.

Network complexity

Connections between ecological components is the second aspect of the complexity definition and are vital for functioning ecosystems.

Network complexity considers how diverse the between-species interactions are within an ecosystem. These interactions include feeding and foraging relationships between insects and plants (herbivory and pollination), predation and mutualism. The diversity of these interactions is assessed through connectance, nestedness and generality. High connectance is associated with robustness to species loss.[31] Generality can indicate how resilient a system is to a loss of species through changes to environmental conditions.[32]

The presence of different areas of woodland within 1km, for example, can boost site network complexity. When a woodland restoration site is close to other woodlands, there are a greater number of connections between species as well as higher nestedness and generality – the woodland has greater resilience and stability. The presence of other habitat patches helps invertebrate movement and colonisation of new woodland patches.[32]

There is evidence that close proximity of other grasslands (within 1-2 km) does not necessarily result in a more complex network, but it does help colonisation.[28, 32] Species arriving from nearby tend to have similar types of interactions as those species already present, contributing to functional redundancy. However, the presence of grasslands in the wider landscape (beyond 2 km) leads to stronger and more complex networks. Pollinating species found in grasslands are highly mobile, travelling long distances to forage and often breeding in other habitats.

Soil microbial complexity

Healthy and diverse soils are important to ecosystem functions 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. Research from RestREco is currently underway to identify drivers of soil microbial community complexity or diversity. Early indications suggest these include former land use, soil pH and age of restoration, restoration method and management.

2.4.3 Complexity drivers

RestREco research has identified multiple key drivers of complexity that are important for the success of restoration efforts. Some of these influences are consistent across multiple habitat types.

Age or length of time

Age or length of time since restoration began is a major driver of structural and interaction diversity in woodlands and grasslands.[28] Older sites have had time to develop a complex structure, and the habitat features that are slow to develop, including trees of different sizes and ages, patches of low vegetation density, open areas, bare ground, multiple canopy layers, veteran trees and dead wood.[32] Older sites have also been exposed to more colonisation events by invertebrates and other species and as a result tend to support more complex plant and animal communities.

Certain habitat features, such as specific host plant species or groupings, can take a long time to develop so invertebrate species associated with these may only be seen on sites of a certain age.[33] Increasing colonisation sees greater competition for resources, leading to greater specialisation or invertebrates seeking new niches in a bid to avoid competing. This can result in novel interactions and further network complexity.

Network complexity in sites of an intermediate age may not be as high due largely to these sites undergoing a process of reorganisation and transition when it comes to plant and invertebrate species composition, with reductions in the abundances of early-successional species.[32]

Size

Site size can also affect complexity. If a site is larger, it has the space to support more microclimates, niches and larger and more diverse populations of plant and animal species. More diverse communities, particularly in invertebrates, leads to more species interactions and greater network complexity.

There is evidence that larger woodlands have higher species abundance and diversity, and horizontal structural complexity with some exceptions.[28, 34] Larger woodlands can also support greater structural complexity as they have the space to support a range of habitats and niches.[34]

Site restoration decisions

Decisions made at the start of restoration can affect complexity. This includes selecting sites based on the previous land use (for example industry or agriculture) for woodlands and the richness of the seed mix used to kickstart a grassland restoration. Former industrial sites need extra support to generate into structurally complex woodlands but may support more complex soil bacterial communities. Establishing grasslands with richer seed mixes tends to result in a complex plant community that develops quicker than if the seed mix used contains fewer species.[28]

When considering the total number of bacterial taxa, grasslands established by planting of seed mixes or green hay tend to have more diverse bacterial communities than those that rely on natural regeneration or lower intervention. But when phylogenetic differences between species are taken into account (i.e. how far away species are from one another on the tree of life) natural regeneration shows higher diversity within a single ecosystem.

Ongoing management

Continued sustainable management has been shown to maintain structural complexity, higher biodiversity and overall favourable condition in a well-established woodland or a woodland undergoing restoration.[35, 36] It also supports greater resilience, multifunctionality and improved biodiversity.[34, 37]

The use of traditional management techniques such as pest and disease management, coppicing and pollarding (woodlands), and livestock grazing (for grasslands) creates structural complexity and supports natural regeneration.

As well as supporting plant diversity, continued low-intensity grassland management is vital for a diverse and resilient interaction network. If management is reduced, for example if grazing activities are removed, this can reduce the generality of pollinator networks, that is each insect species interacts with fewer plant species. This is largely associated with reduced plant species richness. Specialist pollinators can then be lost as the plants they rely on are lost. These mechanisms can increase the risk of functional loss if species are lost under environmental change, affecting the overall resilience of the grassland.[38]

Habitat mosaics

At a landscape scale, biodiversity or species complexity is driven by having a heterogenous landscape, that is it contains a variety of different habitats (habitat mosaics) and multiple land cover types, even if some of those habitats are human modified. This supports the existence of multiple and varied ecological communities across a wider area, even if some individual sites within modified landscapes have reduced within-site diversity. However, retaining natural habitats in a modified landscape is vital to avoid severe decreases in biodiversity.[39]

Having multiple habitats on the same site where woodland is accompanied by pasture or grasslands for example, is also a marker of structural complexity. This complexity supports different suites of species across a site, increasing overall biodiversity and functional diversity. Habitat heterogeneity on a site also provides a range of different environmental conditions and microclimates that can buffer species against the risk of extinction or decline under a changing global climate.[40] Habitat mosaics consisting of a range of land cover types over a landscape, allows multiple ecological communities to form, supporting landscape-wide diversity.

2.4.4 Measuring complexity

Complexity has been identified as a desirable aim for healthy and resilient ecosystems; however, evidence from the RestREco project shows that it cannot be captured by a single metric or indicator.[28]

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.

Current methods of measuring complexity

Current methods and existing data that are in common use in conservation and restoration best practice could be adopted to measure different aspects of complexity. Biodiversity or species complexity measurements already in use at various spatial scales include alpha (number of species per site), beta (differences in biological communities between sites) and gamma (total species richness across a landscape or region) diversity. These indicators can provide insights into how biodiverse, multi-functional, and therefore resilient, a specific site or region is to environmental change and can also be used to assess if there are any shifts in the abundance of species that are local to a specific area in favour of more widespread species.[39] Data sources that can be applied to measuring species complexity for particular phyla include the National Plant Monitoring Scheme, Breeding Bird Survey, Pollinator Monitoring Scheme, UK Butterfly Monitoring Scheme and the British Bat Survey.[41, 42, 43, 44, 45]

Structural complexity can be assessed by using measurements for tree diameters at breast height and standard deviation. Metrics that are included in the National Forest Inventory Woodland Ecological Condition framework, can also be co-opted for structural complexity assessment. These include age distribution of trees, amount of open space, number of vegetation layers (vertical structure) and volume of dead wood.[46] The presence of pressures that reduce overall complexity (invasive plant species, pests and diseases, herbivory/squirrel damage) which can be measured are also relevant to structural complexity. For other habitat types, such as grassland, variation in sward height, amount of bare ground, and plant cover are associated with structural complexity. Satellite imagery and LiDAR (remote sensing) data can be used to assess structural complexity at a landscape level.[23]

Bioacoustics or measuring ecological soundscapes is an area of research that has gained traction in recent years. Soundscapes have been put forward as proxies for ecological complexity.[22] These sounds can come from animals, humans/machinery and natural processes such as wind and rain. A strong link between soundscape complexity of birdsong and structural complexity has been established in woodlands.[47] Bioacoustics can also be used to assess whether there are any changes in habitat vegetation structure or species and has been used to determine bird species richness.[23, 48]

Other methods of measuring complexity include environmental DNA (eDNA) which can be useful for assessing the diversity of soil bacteria and fungi, using species distribution data to determine landscape food web complexity, and eddy covariance to assess carbon fluxes.[23]

2.4.5 The relationship between complexity and ecosystem function

Complex communities that promote high functioning and functionally diverse ecosystems are key to promoting wider ecosystem resilience.

Functioning and resilient ecosystems are not dependent on restoring historical species composition or species identity. Ecosystems can maintain functionality even if species identity changes while restoring

ecological function does not require the recreation of reference communities, which may not be possible under climate change. Research has shown that reinstating half the species from an ecosystem can result in restoring around 75% of function, beyond which, functional redundancy increases.[49]

There is evidence that ecosystems with community and structural complexity have greater multifunctionality and functional redundancy allowing ecological functions to be maintained despite species declines or environmental disturbance.[7, 18, 49]

Biodiversity also secures ecosystem function through facilitation. This is where species improve conditions or provide resources that benefit other species. Structural diversity provides a greater range of habitats and niches.

Biodiversity increases resistance to disturbances such as drought and invasive species and supports community stability.[7]

Ignoring the importance of biodiversity to ecosystem services we rely on comes at multiple costs: the cost of energy and chemical interventions to promote agricultural productivity under environmental change, disturbances, and the loss of crops to pests and diseases. Such systems lack resilience and are more vulnerable to severe changes. Biodiversity can be incorporated into ecosystems managed for human benefit including promoting genetic diversity of crops to reduce the risk of loss to diseases and climate variation, using legumes in crop rotation to increase soil nutrients, and promoting plant diversity and productivity to increase carbon sequestration.[18]

A flexible, complexity-centred approach to ecological restoration not only supports greater functionality and functional redundancy but also contributes to long term ecosystem and habitat resilience. Species targets are still relevant, for example to designated features in SSSIs, but are not the only way.

3 Implications for ecological restoration practice

We are facing challenges around restoring the world's ecosystems under a rapidly changing climate. Relying on old models, where restoration involves bringing back communities that existed in the past, is likely to set us up for failure as environmental conditions become unsuitable for those species.

Restoration efforts should be based on creating complex systems that are multi-functional at multiple spatial scales and are resilient (they have the means to resist, recover, adapt or transform to a robust state) under future change.

Although the actions taken will be different depending on the ecosystem, the principles are the same: promote or maintain multiple aspects of complexity through sustainable management and a flexible approach.

3.1 Existing good practice that aligns with complexity/resilience

Although there is still much focus on recreating reference systems during restoration and resisting changes in species composition in already established systems, several existing frameworks and sources of practical guidance identify complexity and biodiversity as important. Many of these guidelines also address the multiple pressures that are being faced by UK ecosystems, and which also threaten complexity.

Natural England incorporates different aspects of complexity within its woodland and grassland management guides.[50, 51, 52] For example, a combination of short sward, taller vegetation clumps, areas of bare ground and scrub is recommended for grasslands. Other guidance that supports or promotes complexity is tailored to site age and restoration stage. The Woodland Trust's Woodland Creation Guide advises integrating structural complexity at the woodland establishment phase.[53] It also places woodland creation in the context of supporting and enhancing natural capital. More recently, Defra has released guidance on reducing deer populations, a major pressure on woodland complexity and plant diversity.[54] Plantlife's Good Meadow Guide advises regular cutting or grazing to maintain species diversity.[55]

Frameworks exist that measure habitat or ecosystem health through the lens of complexity. Natural England's Favourable Conservation Status (FCS) is defined as "the situation in which a habitat or species is thriving throughout its natural range and is expected to continue to thrive into the future".[56] Its definition and principles support acting for complexity and resilience, consider ecological functions and processes within its framework, and move away from using historical values or reference years during conservation.

3.2 Adaptive management approaches

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.

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. RAD is being actively used by multiple organisations including the United States Geological Survey, the United States National Park Service and Parks Victoria in Australia.[57, 58, 59] The key underlying principle is to acknowledge uncertainty, act despite that uncertainty, and learn from the outcomes to reduce uncertainty. It is a learning-based decision-making cycle where actions and targets are based on lessons learned from previous decisions.

Resilience-Accommodation-Transformation is another adaptive management approach. Adaptation by transformation aims to move a system to an altered state that is 'better suited to changing circumstances' while accommodation, as with RAD's Accept, aims to accept inevitable change rather than promote it.[19]

3.2.1 RAD approach

The purpose of the RAD framework is to help identify potential decisions which allow practitioners to resist, accept or direct trajectories of change. It encourages practitioners to think beyond resistance and consider ways they can actively influence the trajectory of change.[60] There is a great deal of similarity between this framework and Forest Research's Resilience Implementation Framework.[21] The three approaches are:

1. **Resist:** Maintain the current or historical ecosystem structure, composition, processes and functions. Aims to prevent disturbances from impacting the system or helps the system absorb the impacts without change.

2. **Accept:** Yield to ongoing transformations and accept the ecosystem structure, processes and functions that emerge from transformations and disturbance.

3. **Direct:** Practitioners take an active role by steering the changes in ecosystem structure, composition and processes towards a preferred new condition that still maintains functionality and ecosystem services.

By adopting the RAD framework, there may be a need to accept trade-offs. For example, resisting may require spending more resources, including financial, at the cost of other projects and may fail in the long run. What approach is taken may depend on what is driving the change in the ecosystem and the designation of the site that is being managed. Some pressures are outside the land manager's control, for example, climate change and atmospheric nitrogen deposition. In that situation, actions which aim to resist change may not be appropriate, unless the relevant site is in a designated area such as a SSSI. In that case, a site must be managed for a particular set of features, which can limit management interventions. Other constraints can be cultural, related to policy or stakeholder interest.

Examples of actions that could be seen to be related to adaptive management include the removal or movement of sea defences to allow natural processes to reshape coastlines and create new intertidal habitats in response to rising sea levels, species translocations, and accepting the decline of a culturally and economically significant fish species in response to warming lake waters.[19, 61]

3.3 Applying adaptive management

Knowing whether to resist, accept or direct change at any given time requires knowledge of the site undergoing change and the ability to identify potential threats to site features. A full description of how adaptive management frameworks can be applied in practice can be found in supplementary document (Managing for ecological complexity).

Various organisations have set up frameworks and adaptation plans that provide a structured means of bringing together everything that is known about a changing system and its threats with potential routes that can be taken to address those issues.[30, 62, 63]

The essence of applying adaptive management can be distilled into the following:

Know the site or system

– What is the system and what are the site/system features?
– Objectives for site or system
– Spatial and temporal scales

Know the threats

– What threats are challenging site resilience?
– Level of control over identified threats
– Scale – spatial and interactions
– Consequences of threats for specific features and ecosystem services

Identify the level of acceptable change

Identify pathways and management actions for desired outcomes

– Identify
– Evaluate
– Prioritise

Monitor and learn

– Determine whether triggers have been met and when to switch between RAD pathways.

4 Case Studies

4.1 Phytostabilisation of metalliferous mine spoil and revegetation

Provided by Mark N Carey FRICS

A major project to stabilise and revegetate the Garrigill spoil tip in Cumbria was undertaken between 2021 and 2026 by the Mining Remediation Authority (MRA) and the Environment Agency as part of the Water and Abandoned Metal Mines (WAMM) Programme.

WAMM aims to half the length of rivers polluted by harmful metals from abandoned metal mines by 2038 to meet Environmental Improvement Plan 2025 targets. The project focuses on removing dissolved metals from mine water and reducing pollution to prevent metal rich sediment entering river catchments.

Historical mining has left a visible legacy on the landscape, including spoils containing heavy metals. Eroding sediments from unvegetated spoils on steep slopes next to watercourses are damaging river catchment ecosystems. The Garrigill spoil tip, which is within the North Pennines National Landscape and the River Tyne catchment contains around 60,000 tonnes of spoil, including more than 1,400 tonnes of lead, zinc and cadmium. Before 2020 around three tonnes of this spoil was eroding annually into the Garrigill Burn, a tributary of the River Tyne.

In novel ecological reconstruction trials, surrogate soil was created to sustain pioneer vegetation growth to support natural soil and biocrust formation. Research found that water availability inhibits vegetation establishment on contaminated, soilless substrates more than metal toxicity.[64] Ecosystem processes including photosynthesis, water infiltration, soil formation, nutrient recycling, and community dynamics for species complexity were harnessed in an adaptive restoration approach. These processes, alongside surrogate soil, supported plant community establishment via natural succession.



2018 prior to regrading and culvert repair



Post storms Ciara and Desmond 2020



Hydroseeding in 2023

Following repairs to a collapsed culvert and tip stabilisation work, different surrogate soil formulations were applied to trial plots using hydroseeding. Treatments combined organic matter (bracken compost), biochar, mycorrhizal fungi, seaweed fertiliser, kaolinite and binding agents to improve soil development, nutrient retention and vegetation establishment and for heavy metal adsorption. A pioneer seed mix of grasses and herbs was applied to promote slope stability and nutrient cycling. In addition, a metal-tolerant calaminarian plant community, translocated from the site in 2019, was established on regraded spoil elsewhere. It contained spring sandwort (*Minuartia verna*), thrift (*Armeria maritima*), alpine pennycress (*Noccaea caerulescens*) and sheep's fescue (*Festuca ovina*).

Following poor vegetation establishment, all but three plots were re-treated in 2023 using locally sourced green waste compost. Successful plots had thicker compost application, biochar addition, and, in one plot, coir erosion matting. Subsequent refinements, including thicker surface applications, biochar inoculated with compost teas, and basalt rock dust, improved vegetation establishment and cover, although drought stress in 2025–2026 highlighted challenges in balancing water retention and plant demand. Willow (*Salix viminalis*) fascines and alder (*Alnus glutinosa*) planting have stabilised eroding spoil, while contributing to heavy metal immobilisation and nitrogen fixation.



Vegetation cover in 2025



Bird's-foot-trefoil (*Lotus corniculatus*) in flower 2026



General view 2026







From spoil to soil 2021 – 2025

The project has demonstrated early soil development, root growth, soil aggregation, the appearance of worms for nutrient cycling, and moss and lichen biocrust formation. A diverse mosaic of plant communities is emerging in response to changing site conditions, with varying moisture regimes from variations in vegetation cover, surface roughness and exposed rock creating opportunities for greater biodiversity and potential colonisation by calaminarian vegetation.

Summary

The site is in the early stages of ecological succession and remains vulnerable to drought, heavy rainfall and rabbit disturbance. Water stress has been the main challenge to vegetation establishment, while succession is unpredictable and non-linear. Drought has contributed to a mosaic of vascular and non-vascular plant communities, increasing ecological complexity and supporting the return of invertebrates, birds and mammals, alongside improvements in downstream water quality. A calaminarian plant nursery has also been established in the North Pennines to support research and provide seed sources for future mine restoration projects.

This research project was funded by the Department for Environment, Food and Rural Affairs (Defra) via the Mining Remediation Authority, as part of the WAMM Programme. The WAMM Programme is a partnership between the Environment Agency, the Mining Remediation Authority, and Defra. The views expressed in this case study are those of the author and do not necessarily reflect those of any other supporting organisation.

4.2 Increasing Habitat Complexity of a Broadleaf Plantation

Leedham Woods is an immature broadleaf plantation within the National Forest, established in 2003. It is part of the transformation of the landscape around Overseal from industry and agriculture into a mixed forest habitat.

Much of the young woodland was even aged and uniform in height and density with a closed canopy and narrow rides. This limited the range of structural differentiation, light levels, woodland edge, dead wood and ground-layer habitats available for flowering plants, scrub and invertebrates and birds. Primary species include English oak (25%), European ash (20%), sweet chestnut (15%) and wild cherry (8%).

Management focused on increasing habitat complexity, selective thinning to open the canopy, and reducing the impacts of pests and disease such as ash dieback. Rides and woodland edges were widened and scalloped to create graded transitions from open grassland through scrub edge and up into the woodland canopy. Small glades were re-opened or created to improve light and structural diversity. Some of the arisings were removed for fuelwood, with some retained as habitat piles where appropriate. Standing dead wood was created through ringbarking, to provide niche opportunities.



Ride edge thinning/coppicing - before



Ride edge thinning/coppicing - during



Ride edge thinning/coppicing - two years after



Scallop creation and ride edge thinning - before



Scallop creation and ride edge thinning - during



Scallop creation and ride edge thinning - two years after

The site is developing a more varied structure, open canopy and variation in light levels with a more open ride network, natural regeneration and improving conditions for ground flora, birds and invertebrates, plus habitat for fungi, beetles, small mammals and birds. Future works hopes to further develop habitat complexity.

Challenges have included improving habitat diversity at an appropriate speed, without opening a young woodland too quickly or losing canopy health and compromising future resilience. Work has been targeted and phased, dense areas retained for shelter and the canopy gradually opened elsewhere. Phasing has moved around the site to avoid a linear approach of age and structure. Browsing pressure from roe (*Capreolus capreolus*) and muntjac (*Muntiacus reevesi*) deer is being monitored and will be addressed in follow-up management, with control and protection of coppice when required.

5 Policy and legislation: background and recommendations

Protected areas (PAs) remain the foundation of biodiversity conservation and continue to deliver better outcomes for wildlife than many surrounding landscapes. However, biodiversity loss is continuing despite decades of policy-setting, while current approaches are not keeping pace with accelerating environmental change.

The traditional conservation model, built around maintaining protected sites in a fixed historical condition, is becoming increasingly difficult to sustain. Future protected area systems must therefore focus not only on protecting existing biodiversity but also on enabling ecological adaptation, resilience and recovery. Within such systems ecological complexity, as identified by RestREco, can facilitate these outcomes by supporting multifunctionality and biodiversity.

Creating these systems requires a transition from managing individual sites as isolated units towards designing coherent ecological networks of larger, better connected and more resilient habitats. PAs should form the core of these networks, supported by restoration-focused landscapes, buffer zones and permeable land uses that facilitate species movement and adaptation to changing climatic conditions.

5.1 Protected areas: successes and emerging limitations

PAs have been central to conservation policy for over fifty years. International frameworks such as the Ramsar Convention (1971) established networks of sites to protect species, habitats and ecosystems of national and international importance. Evidence demonstrates that PAs continue to support higher levels of biodiversity and ecological integrity than many surrounding landscapes, providing refugia from intensive land use, maintaining viable populations and supporting ecosystem services.[65] They often act as source areas for recolonisation and range expansion.[66, 67]

In the UK, PAs are often too small, fragmented and isolated to support biodiverse and resilient ecological systems, while ongoing pressures from agriculture, urbanisation, pollution, invasive species and climate change continue to erode ecological condition.[68, 69, 70, 71] Other challenges to the integrity of PAs include a lack of enforcement against environmentally damaging activities and neglect on many sites.[72] PAs have historically been designated as representative examples of biodiversity rather than components of a functioning ecological network, limiting options for a whole-system approach to nature conservation that strengthens and sustains ecological processes, connectivity and functional relationships.

RestREco's philosophy directly challenges this requirement for individual protected areas to contain specific sets of species or habitat structures. It argues that shifting environmental and climatic conditions means recreating systems of the past is no longer appropriate. Instead, a function-led approach that aims for complex ecosystems on sites that are legally protected and have strong ecological connections is more likely to lead to a more resilient nature landscape.

5.2 Climate change and the need for a new conservation paradigm

Many PAs were designated on the assumption that species and habitats could be maintained indefinitely in a desired historical state. This assumption is increasingly challenged by climate-driven shifts in species distributions, ecological communities and environmental processes such as hydrology and growing recognition of novel ecosystems.[73]

As anthropogenic environmental change accelerates, future success will depend less on maintaining static ecological states and more on sustaining ecosystem function and adaptive capacity to be resilient to such changes. Therefore, evidence suggests conservation objectives should focus on restoring resilient ecosystems capable of accommodating ecological change rather than attempting to recreate historical conditions and species assemblages across all landscapes. RestREco's findings suggest that achieving these conservation objectives can be supported by actions that facilitate and promote ecological complexity and biodiversity as these provide the foundations for resilient and functioning ecosystems.[23]

The principles established by Sir John Lawton's Making Space for Nature remain highly relevant.[68] They look beyond nature recovery towards sustaining enhanced ecosystem biodiversity, function and resilience under ongoing environmental change and human pressures. Ecological networks should be:

> **– More extensive;**
> **– Bigger in scale;**
> **– Better managed; and**
> **– More joined-up and connected.**

Ecological networks based on these principles expand a landscape's capacity to support future biodiversity and species' ability to respond to climate change. More sites mean that there are more places for nature to thrive or for species to migrate to as environmental conditions change. Larger sites have greater adaptive capacity and, as RestREco shows, often have more complex and resilient species networks and support greater structural variation, which in turn promotes biodiversity. Sites which are appropriately managed are more structurally complex, biodiverse and support larger species populations. Well-connected networks contribute to more permeable landscapes, supporting species dispersal and recolonisation, range shifts, and more complex species interaction networks. These in turn contribute to long-term resilience under changing environmental conditions.

Instead of considering PAs as isolated units therefore, future conservation systems should instead be planned as integrated networks comprising:

> **– core protected areas;**
> **– buffer zones;**
> **– restoration landscapes;**
> **– ecological corridors and stepping stones; and**
> **– areas managed to support species movement and adaptation.**

Within such a network, ecological complexity could be used as an explicit restoration metric. The characteristics of complex ecosystems – diverse plant and animal communities, microhabitats, structural variation and robust ecological interactions at multiple trophic levels – support genetic and functional diversity, ecological niches and climate refugia, adaptive capacity and multifunctionality. Using ecological complexity as a metric could steer restoration and conservation policy towards ensuring ecosystems have the capacity to persist and thrive under accelerating change. This may be a more robust indicator of long-term ecological recovery and resilience than progress towards a historical reference state or a specific species assemblage.

5.3 Nature Nuclei and climate-smart conservation

An emerging vision is the concept of Nature Nuclei, in which PAs act as reservoirs of biodiversity from which species and habitats can expand into the wider landscape.[68, 74] These nuclei become the core components of a broader nature recovery network where maintaining ecological function and biodiversity value is more important than preserving fixed species assemblages. Management which looks to promote structural, species and network complexity could contribute significantly to creating multifunctional and biodiverse nuclei and networks.

Within these nuclei, particular attention should be given to identifying and protecting **climate refugia**. These are areas characterised by features such as:

– high environmental heterogeneity;
– complex topography;
– hydrological integrity; and
– stable local climatic conditions.

Such locations are likely to play an increasingly important role in supporting biodiversity persistence and adaptation under climate change, particularly for more vulnerable species.

5.4 Applying the Resist, Accept, Direct Framework

The Resist-Accept-Direct (RAD) framework provides a practical decision-making tool for conservation under environmental change. It incorporates approaches that support responsive and forward-thinking management of protected sites:

Resist

Interventions aim to maintain existing ecological conditions where globally important species, habitats or ecosystem functions are at risk.

Accept

Management recognises that some ecological changes are unavoidable and focuses on maintaining ecosystem integrity during transition.

Direct

Interventions actively support adaptation, ecological transformation, restoration, species colonisation and the development of future biodiversity opportunities.

Together, these approaches move conservation beyond a singular objective of restoring historical conditions and provide a flexible framework for managing ecological function and structure in a changing environment.

5.5 From site condition to ecological resilience

Current monitoring systems largely assess whether designated features are present and maintained. While important, this approach is insufficient for managing ecosystems under dynamic environmental change.

Future monitoring frameworks should increasingly measure:

- **ecological function;**
- **habitat connectivity;**
- **structural complexity;**
- **adaptive capacity;**
- **ecosystem resilience; and**
- **ecosystem service delivery.**

The concept of **Favourable Conservation Status (FCS)** offers a useful model. Unlike traditional feature-based assessments, FCS focuses on whether species and habitats are thriving across their natural range and are likely to remain viable in the future. It explicitly incorporates ecosystem function, resilience and long-term ecological potential.[56] Parameters used to define FCS for habitats identify structure and function as key properties which should be interpreted and evaluated. Specific structure attributes outlined in FCS include components associated with structural complexity for example bare ground, vegetation structure and plant communities.

Within a decision-making framework, like RAD, evidence from monitoring resilience-associated metrics should be used to continually refine management interventions as conditions change. There are also opportunities for Biodiversity Net Gain (BNG) to go beyond habitat-based metrics and to incorporate targets around ecological function and resilience. BNG sites are currently assessed on habitat area, distinctiveness and condition, based on the assumption these are an adequate representation of biodiversity value. While these metrics are important, there is little consideration of ecological complexity, function and resilience. Additionally, BNG requires that enhanced or created sites are secured for at least 30 years. However, changing environmental conditions are likely to threaten the long-term resilience of BNG habitats.[75] A better approach to BNG site planning and maintenance could incorporate early identification of climate change risks, resilience measures to buffer the effects of climate change, and habitat features which support ecological function, structural complexity and biodiversity.

Consistently monitoring the performance of resilience measures and how habitats are responding to changing environmental conditions could help identify any further measures that may be needed to support BNG habitat health, function and biodiversity.

5.6 Protected areas as natural infrastructure

PAs should increasingly be recognised as a form of national adaptation infrastructure. Beyond biodiversity conservation, they provide significant societal benefits by:

- **storing carbon;**
- **regulating water flows;**
- **reducing flood and drought risks;**
- **supporting soil stability;**
- **maintaining ecosystem resilience; and**
- **improving human health and wellbeing.**

Provision of these societal benefits hinges on protected areas being diverse and highly functional, characteristics that are strongly tied to structural, plant and network complexity.

The Dasgupta Review emphasised that economies are embedded within nature and that biodiversity represents a critical form of natural capital.[3] In this context PAs should be understood as long-term public investments that support inclusive wealth and societal resilience. Conversely, deterioration of PAs represents the depreciation of nationally important natural assets.

5.7 Governance and delivery

Effective conservation ultimately depends on people. Future ecological networks will require collaboration between:

- **landowners and farmers;**
- **local authorities;**
- **PA managers;**
- **statutory agencies;**
- **environmental NGOs;**
- **local communities; and**
- **civil society.**

Governance arrangements should emphasise participation, co-design, transparency and long-term stewardship. Building social resilience is as important as enhancing ecological resilience. Long-term delivery would benefit from a coordinated national strategy, supported by clear and ambitious targets that focus on function and complexity, adequate funding, adaptive monitoring and landscape-scale governance structures.

5.8 Policy Recommendations

Future policy should:

- **Expand PAs strategically to create larger and more coherent ecological networks.**
- **Improve the condition, resilience and ecological function of existing protected sites and incorporate ecological complexity as a metric.**
- **Identify, safeguard and connect climate refugia.**
- **Strengthen landscape connectivity through restoration, stepping stones and buffer zones.**
- **Integrate PAs within wider Nature Recovery Networks.**
- **Embed biodiversity and natural capital within economic decision-making.**
- **Align biodiversity conservation with climate adaptation policy.**
- **Adopt adaptive management and resilience-based monitoring frameworks.**
- **Increase investment in ecosystem restoration and long-term stewardship.**
- **Recognise PAs as strategic national infrastructure that delivers biodiversity, climate and societal benefits.**

5.9 Summary

Protected area policy is entering a period of fundamental transition. While PAs remain essential for conserving biodiversity, they can no longer be viewed solely as static repositories of species and habitats. Instead, they must function as dynamic components of a wider ecological network that supports adaptation, resilience and recovery in a rapidly changing world.

Future-focused conservation should place biodiversity recovery at its heart while enabling ecological change where necessary. By treating protected areas as Nature Nuclei, strengthening ecological networks, embracing adaptive management and investing in restoration, policymakers can build a resilient natural environment capable of supporting biodiversity, climate adaptation and long-term societal prosperity.

6 Conclusion

The challenges of locked-in climate change and unchecked biodiversity loss are recognised globally, with ecological restoration providing a key solution.

The RestREco research supports emerging best practice that refocuses the aims of restoration away from recreating past habitats and ecosystems, towards creating the conditions under which complex, functional and resilient ecosystems can develop. The project also brings new insight around approaches to measuring the progress and success of restoration, supporting a move away from a restricted set of metrics to measuring multiple aspects at multiple scales. The outcome being the creation of ecosystems that are able to withstand disturbance, adapt to change and continue to provide benefits into the future.

The research has identified key aspects of complexity (structural, plant community, network and soil microbial) that are strongly associated with ecosystem resilience and a number of complexity drivers that are important for the success of restoration efforts.

The information gathered to date from the RestREco project can be applied by land managers and restoration practitioners, through adaptive management approaches that go beyond resistance to change.

At a national level the findings are important for UK policymakers, providing evidence to challenge and broaden restoration approaches and targets that focus on rare or threatened species and associated habitats, or habitat compensation and offsetting linked to development. The research highlights the value of considering ecosystem complexity, function and resilience in relation to restoration success.

6.1 Next steps – knowledge gaps and priorities

RestREco is a comprehensive project that examined the potential for complexity and resilience to be major targets for nature recovery. One key finding is there is no single, simple indicator for complexity. RestREco research established that links between different aspects of complexity were limited with only a few key correlations (structural complexity and invertebrate complexity for example). This means there is no single, primary action to boost overall complexity and instead a raft of targeted measures is required. Further research could examine how complexity could be distilled into a set of key metrics to enable practitioners to narrow management focus or to provide a focal point around which complexity targets could be set.

Although research from RestREco focused on woodlands and grasslands, similarities between the two habitat types during restoration such as the importance of starting context would indicate the principles for managing for complexity can be applied to other habitat types. Other habitats may have different drivers of

complexity but the underlying principle of combining multiple complexity indicators should still be relevant. Applying this approach to heathland or wetland systems for example may give interesting insights into how applicable it across ecosystems.

Although there are many documented cases of decision-making frameworks such as RAD being used in the field, many are associated with landscapes and national parks in the United States and Australia, which are usually much bigger than those found in the UK and Europe. There are encouraging signs of adaptive management-style principles being used in the UK, although the examples we provide do not necessarily refer to those actions as 'adaptive management'. A more widespread adoption of RAD or adaptive management may help to answer questions as to how UK species, habitats and landscapes respond to managing for change in this way.

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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.
Biodiversity loss	The decline or disappearance of species, genetic diversity, habitats or ecosystems.
Components	The individual elements or parts that make up a system.
Connectance	The proportion of possible interactions between species that actually occur within a community or network.
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.
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 diversity	The variety of ecological functions and traits performed by different species within a community or ecosystem.
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.

Term	Definition
Generality	The extent to which a species interacts with many different species, with higher generality indicating a broader range of interactions.
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.
Insurance effect	The ability of species diversity to help an ecosystem maintain its functions when environmental conditions change or species decline.
Natural capital	The Earth's stock of natural assets that underpin ecosystem services.
Natural Environment Research Council (NERC)	A UK research council that funds and supports research into the natural environment.
Nature nuclei	Areas that have played and are still playing a key part in maintaining nature, and that have the potential to form the basis for future conservation action and to spread to other areas.
Nestedness	Used to assess the stability or resilience of a network. The extent to which specialist species interact with subsets of the species that generalists interact with, creating a nested pattern of interactions within a community.
Network complexity	The diversity of between-species interactions within a habitat or ecosystem.
Recovery	The ability of a system or function to bounce back after a disturbance.
Resilience	A system's ability to recover from or withstand disturbance without a loss of function or falling into a degraded or undesirable state. A system's ability to resist, recover, adapt or transform to a robust state.
Resilience-Accommodation-Transformation	An adaptive management approach.
Resistance	The extent to which a system or function declines during a disturbance.
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.
Shifting ecological baselines	A change in perception, standards or reference points of what is considered a normal or healthy ecosystem over time.
Site of Special Scientific Interest (SSSI)	A protected area designated for its important wildlife, habitats, geology or landforms, and managed to conserve its scientific interest.
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.
Sustainable Development Goals (SDGs)	Global goals established by the United Nations to address major social, economic and environmental challenges and promote sustainable development by 2030.



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