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Biodiversity for agriculture: the role of integrated farm management in supporting agricultural production through biodiversity

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1 Introduction: biodiversity for agriculture and integrated farm management

This chapter examines the links between agricultural management and biodiversity, mainly at the scales of the farm and field. Farms range in size from small holdings to vast tracts of land, but all have similar origins and face similar challenges. Agriculture originated from the conversion of natural vegetation to systems that are repeatedly disturbed to grow crops and grazing. Much original

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biodiversity was lost in that conversion, but agricultural ecosystems still operate through the same fundamental biophysical processes as natural ecosystems, based on flows of energy and matter (Norman et al., 1984; Vasey, 1992; Sinclair and Weiss, 2010), all mediated by biodiversity (Squire, 2020).

The first part of this chapter (Sections 1–4) sets the context in which farm- and field-scale management can work to regenerate and sustain agricultural ecosystems. A central part of the chapter (Sections 5–9) sets out the main principles governing the design of sustainable and regenerative practices. The final part of the chapter (Sections 10–11) offers some practical approaches, including a case study showing the application of design principles in a particular landscape.

Living organisms mediate every process in agricultural production. The organic matter they make and leave combines with mineral particles to form soil. Without soil, there would be no agriculture and little life on land (Ball, 2022). Organisms form complex trophic webs comprising wild plants, the soil microbiome, detritus-feeders, pollinators, pests and their natural predators, pathogens of crops and livestock and higher organisms, all living within managed crops and grass (Norris and Kogan, 2000; Hawes et al. 2009, 2021). Much of this essential biodiversity is microscopic or just visible to the eye, therefore unseen and easily missed, but it performs key ecosystem services, including building stores of carbon and nutrients, detoxifying pollutants and fixing atmospheric nitrogen in soil. It has been defined as Biodiversity for Agriculture or B for A (Bàrberi et al., 2010; Bàrberi, 2015) to distinguish it from Agriculture for Biodiversity (A for B), where management acts to support iconic or culturally valued plants and animals, some that are now in decline and facing extinction.

The difference between A for B and B for A is not hard or clear-cut, since most organisms affect agriculture in some way (Squire, 2020). However, the distinction is necessary since there is a tendency in discussion on agricultural policy to consider only or mainly A for B. This chapter emphasises the importance of B for A for achieving balanced environmental and economic outcomes for farming.

The term 'Integrated Farm Management' implies that the various activities on a farm – and hence the biodiversity and ecological processes they affect – work together and complement each other (Holland et al., 1994). Individual compartments, such as fields, orchards, woodlots and grazing, continually interact over space and time. Integrated management implies interchange and circularity in the use of resources. While each compartment must be managed to build and conserve soil, carbon stocks and nutrients, the outputs of one activity should be used to benefit another, e.g. when land is mulched or fertilised from straw, hay and livestock manure (Watson et al., 2002; Lemaire et al., 2017; Ball et al., 2018). Integration over time ensures that production

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in one year is influenced by residual effects from previous years and will, in turn, influence production in future years. Integrated farm management is not a recent concept. Rotation is a long-standing example of temporal integration: one crop might extract nutrients from the soil, while another, such as a legume, regenerates them for the next in sequence. One crop might provide the environment for certain weeds to emerge, while the next might suppress those weeds and stop them from seeding.

Humans nurtured the land and its plants and animals for millennia before formal agriculture began through the domestication of plants around 10 000 years ago (Vasey, 1992; Pearson and Ison, 1997; Cumpston et al., 2022). However, despite examples of sustainable land management that have persisted until today, many examples of poor practice and wrong strategies litter the history of agriculture (Azam Ali, 2021). Failure to appreciate soil, climate and the removal of natural vegetation has been responsible for degrading ancient ecosystems in as little as a few decades (e.g. Bennett, 1935). After the 1950s, the advent of powerful machinery, manufactured fertiliser, pesticides and new crop varieties generated a rise in yield per unit area and allowed profitable crops to be grown more or less continuously (Evans, 1993; Conway, 1997). The rise in agricultural production matched growth in the global human population – a major achievement of science and technology (Kawashima et al., 1997; Keating et al., 2014). But twentieth century intensification led to the demise of many traditional and integrated systems, and concentrated industrial-scale production of a few crop species and varieties (Azam Ali and Squire, 2004; Maxted and Lauvie, 2017; Azam Ali, 2021). The resulting soil erosion, pollution and decline in biodiversity are now a global catastrophe (Doran, 2002; Lal, 2012; Borelli et al., 2013; FAO, 2015).

There is, however, a widespread move to return to spatial and temporal integration (Holland et al., 1994; Leakey, 2012; Ball et al., 2018), but the transition is not simple and straightforward (Syers, 1997). Systems have to be assessed at a range of scales and in relation to present and future stressors whose effects may be highly uncertain (Landis, 2003). Many integrated methods have been lost from memory, while new interventions are needed to restore degraded land and maintain a profitable output without reliance on methods such as intrusive tillage and pesticides.

This chapter continues with a summary of the transitions from natural ecosystems to the various forms of agriculture, the importance of scale and connectedness between local management and global influences, and finally the options for management to modify farmland vegetation. The approach aims to present the principles behind integrated management, using examples from a range of agricultural systems differing in intensity and geographical location.

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2 Transitions from natural ecosystems to differing types of farming system

All agricultural systems originated from forest, grassland, wetland and other natural ecosystems that formed on the earth's surface. The various states before, during and after agriculture are shown schematically in Fig. 1. A primary ecosystem (Fig. 1 box 1) can be moved into 'extensive' production, for example, where animals are herded or hunted and plants nurtured and harvested (Fig. 1 box 2). A primary ecosystem can also be moved into a more controlled form of management where the land is repeatedly tilled or grazed. Where such agriculture has survived for hundreds or thousands of years, it is termed here as 'sustainable' (Fig. 1, box 3; examples in Fig. 2). There are many examples of sustainable agriculture remaining today (Vasey, 1992), ranging from small-scale, multi-species 'forest gardens' in the humid tropics (Conway, 1997; McConnell et al., 2003) to large-scale cultivation of major crops such as wetland rice in east Asia (Falvey, 2000).

In many parts of the world, however, agriculture has become more extractive (Fig. 1, boxes 3–4), for example due to over-grazing by livestock and repeated deep and intrusive cultivation (Dlamini et al., 2014; Owuor et al., 2018; Zalidis et al., 2002). Extractive agriculture, if it continues unabated, leads to loss of soil and exhaustion of the land (Fig. 1, box 5), then to either desertification (in which production is not possible) or reversal to a secondary ecosystem. There are also instances in which a transition from a primary ecosystem to extractive

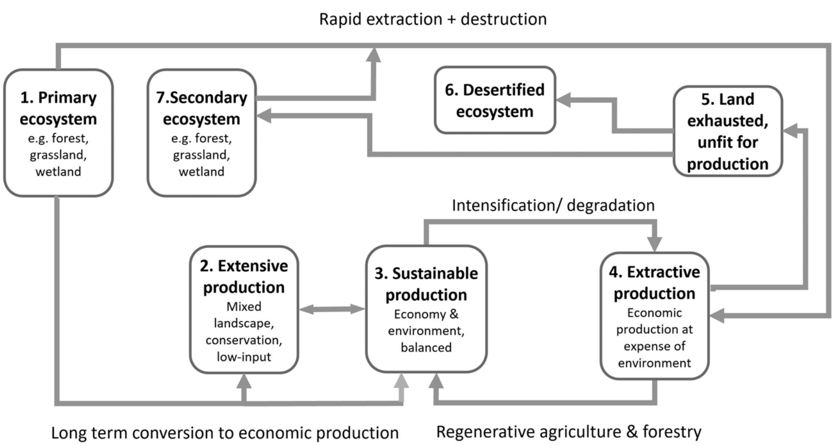

Figure 1 Transitions in land use from a natural ecosystem (1) to systems managed for food and other products (2, 3), which if over-intensified move to a state of extractive production (4). If not reversed (4) leads to land exhausted of resources (5), and then to a desertified system (6) or to a secondary ecosystem if conditions allow regeneration (7). In some forms of agriculture, a primary ecosystem moves rapidly to extractive production (4) and then to (5) and (7), from where the cycle may continue back to (4).

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Figure 2 Examples of long-term, sustainable production systems: (top left clockwise) fruit tree orchards in Greece (2013); wetland rice in northern Laos (2008); small grass pasture fields below forest, Romania (2007); mixed rice, fruit, fodder and grazing, south central India (1977). Photographs by G. R. Squire.

production has happened over a very short period without transitioning through a sustainable state (Fig. 1 arrow boxes 1–4). The US Dust Bowl is an example of such rapid conversion (Bennett, 1935). Some instances of shifting cultivation also sit within this category, in which forest or savannah is destroyed by burning or cutting and crops are grown on the nutrients left in the soil (Norman et al., 1984; Anderson, 1993; McConnell et al., 2003). Typically, the nutrients are exhausted after only a few years (Fig. 1, boxes 4–5), after which the process is repeated on another area of primary or secondary ecosystem. Examples of extractive production in Fig. 3 all show large areas of bare or partly vegetated soil, exposed to rain and wind and prone to erosion.

Given the increasing demands on agricultural space by a growing world population (FAO 2021), there is a greater need than ever to return extractive to sustainable production (Hanjra et al., 2017). This is one of the main roles of integrated farm management.

3 Scales of interaction influencing agricultural systems

The spatial focus of integrated farm management is typically the field and farm, the scales at which basic management decisions are made. However, fields and farms are influenced by factors at a range of other scales (Leakey, 2012; Perfecto and Vandermeer, 2017). The concentric rings in Fig. 4 show spatial

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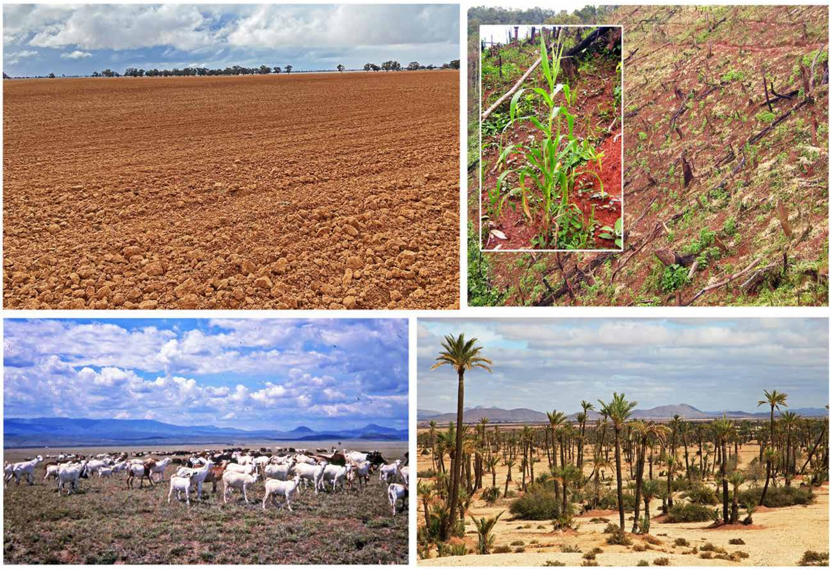

Figure 3 Examples of extractive production characterised by large areas of bare or poorly vegetated soil, prone to damage and erosion: (top left clockwise) tilled field, Victoria Australia (2023); shifting cultivation, land cleared, maize planted, Laos (2008); degraded palm grove, Morocco (2014); grazing on sparse vegetation, East Africa (1989). Photographs by G. R. Squire.

scales most relevant to integrated farming. Farms are subject to markets and policy from local to national and global scales. The choices of what to grow and how to manage it are directly influenced by global demand for a product, by governmental factors such as subsidies and regulations, and by the availability of infrastructure such as processing factories, abattoirs and transport networks to connect farmers to differing markets.

In turn, management of the farm aims for gains (or 'goods' or 'services') in terms of products to be consumed or sold, but also regulation of energy and water, and societal and cultural benefits both for those who work the land and the wider population. Achieving such gains inevitably leads to losses, of soil and pollutants, and of crops and livestock not harvested or not sold. Farming needs to repeatedly assess the outputs and value of the gains in relation to the costs of inputs and losses, consider the trade-offs and adjust practice to maximise gains and minimise losses. Part of this adjustment causes feedbacks to higher scales, e.g. to consider the most effective means of gaining grants and subsidies and complying with regulations.

Fields and farms therefore are far from isolated. The global influences in the outer ring apply to both industrialised and subsistence agriculture, since the latter rarely operates in isolation, being influenced by factors such

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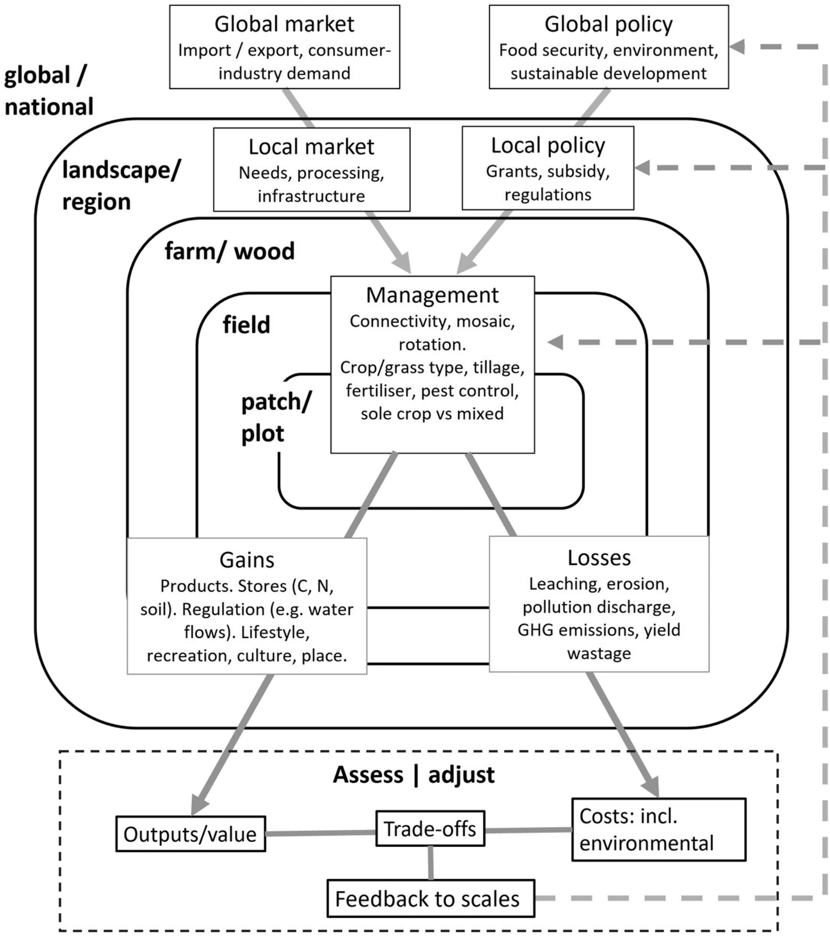

Figure 4 Scales of interaction from global to in-field patch that influence an integrated agricultural system. Diagram adapted from a more comprehensive version by C. Hawes for the Sustainable Crop Systems research programme funded by Scottish Government.

as international aid, global expansion of crops and livestock and the spatial movement of soil and other materials by wind and water.

Whatever other influences there may be, living organisms mediate all management options, gains and losses and the associated processes in the central part of Fig. 4. A 'chain of effect' begins with interventions at field- and farm scales, acts through living organisms which, in turn, modify ecological processes that, in combination, finally determine whether higher-level states are achieved (described at Section 7). Such states include carbon stocks, soil fertility, regulation of water flows, agricultural products, and economic returns.

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This part of the chapter ends by considering the options, mainly in choice of species, genotypes and associated agronomy, that initiate a 'chain of effect'.

4 Increasing species, functional and habitat diversity

Technological developments in agriculture in the last century have been concentrated in a few species: the main grain and tuber crops and, to a lesser extent, the main grasses. The greatest effort in international germplasm collections and breeding programmes has been for maize, rice and wheat. These crops were prioritised because they were able to provide the carbohydrate component of the diet for most of the human population. The thousands of other traditionally grown crop plants have been largely neglected (Azam Ali, 2021). The number of genetic varieties of many of the main crop species have diminished (Maxted and Lauvie, 2017). Similarly, of the thousands of tree species used across the world for a multitude of products, only a few have been subjected to major genetic study for use in industrialised production (Leakey, 2012).

A consequence of this concentration of effort has been the spread of resource-demanding species to new regions. Maize, domesticated in the Americas, spread throughout the world, including to resource-poor regions, where the crop is prone to fail if there is insufficient rainfall and no irrigation (Azam Ali and Squire, 2004). A move to more sustainable production will need to reverse this trend, to include more species, a broader choice of functional types in the main crops, and creation of more diverse farmland habitat.

4.1 More species: lessons from traditional and pre-industrial agriculture

As agriculture re-diversifies and regenerates, it can learn from traditional forms of production and gathering. In north-west Thailand, for example, more than 50 cultivated plant species are typically found in and around a field and, in total, thousands of species are used in the area for food, fibre, medicine, dye, construction, firewood, decoration and ceremony (Anderson, 1993). In the home-gardens of Java, many species are grown in small plots for food, spices, medicines and livestock feed, and 'in intricate relationships with each other', occupying a series of canopy heights from those near the ground to tall forms such as coconut and timber trees (Conway, 1997). Similarly, forest gardens in the Kandy region of Sri Lanka each comprise typically around 40 species, including many trees, growing in a tiered arrangement which mimics the natural forest (McConnell et al., 2003; Perera and Rajapakse, 1991).

Botanical diversity in traditional cultures also resides in the variety of end-products from the main species cultivated. Diversity of product is associated with a wide range of phenology and structure possessed by landraces and

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cultivars. For example, coconut has been grown in semi-wild and in a range of cultivated forms for milk, oil, ointment, vinegar, medicine, livestock 'cake', fibre for matting, palms for thatching, trunk for structure and many other products (Burkhill, 1966). The Australian grass spinifex, in its many forms, has contributed seed-cake, fibre, string, insect repellent, medicinal applications, hafting (joining) metal to handles and shelter (Pitman and Wallis, 2012; Cumpston et al., 2022). The growing and harvesting of a species for such a range of products inevitably raises the number and type of possible interactions that it has with other living organisms.

For integrative or regenerative practice to ameliorate environmental degradation, protect soil and build stores, it will need to displace systems relying on large areas of monoculture with plant assemblages consisting of several species which offer a range of products. As will be described later in the chapter, complex plant systems are better able to regulate the great fluxes of solar radiation and precipitation, use what they need and dissipate the rest.

4.2 Functional diversity in the main crop species

People have relied on maize, rice and wheat for millennia and will continue to need them. However, integrated management should consider reversing the trend in modern technology towards a narrow range of plant form and function (Maxted and Lauvie, 2017). To facilitate harvesting and other agronomic operations, industrial agriculture aims for uniformity among plants in a field. Crop breeding favours determinate and synchronous phenology, mainly in annual forms, traits that ensure most plants in a field mature at about the same time after a well-defined period (Azam Ali & Squire, 2004). With the support of mineral fertiliser and pesticide, management can grow the same species and variety at high plant density year after year. However, systems built around such plants rely on predictable and favourable weather, continued supply of affordable fertiliser, and use of pesticides to prevent proliferation of pests that thrive in such conditions. They may lack resilience and fail if conditions markedly change. A principal mechanism to restore resilience therefore is to increase within-species botanical diversity in terms of plant traits and the configuration in which plants are grown in a field (Azam Ali and Squire, 2004).

Resilience can be enhanced in most crop and grass species by deploying genotypes that are more indeterminate and asynchronous, traits that reduce their susceptibility to abiotic shocks such as bad weather and allow the crop to recover and produce a yield if conditions improve. In addition, species and genotypes may be mixed within a single field, again to reduce susceptibility to unfavourable conditions and to provide more than one product from a field (Willey, 1985). Such mixtures may comprise several genotypes of one crop species (Newton, 2016) or two or more species grown as mixes or intercrops

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Table 1 Examples of crop and grass characteristics that may be deployed within fields to facilitate sustainable or regenerative management, arranged in categories of Genotype and Agronomy, adapted from Azam Ali and Squire (2004) with additional input from Hawes et al. (2021)

Characteristic	Typical problems	Examples of regenerative intervention
A Genotype		
Determinate phenology with synchronous reproduction and maturity facilitate management, especially harvesting	High expected returns reduced or lost if reproductive sinks (grain, fruit) fail or harvesting is disrupted in adverse weather	Species/varieties with indeterminate phenology, maturing asynchronously over a long period, allowing plants to continue yielding when adverse conditions are relieved
Annual genotypes give high and regular economic returns	Annuals produce lower above- and below-ground carbon stores, demand regular soil cultivation, and thereby increase soil exposure and erosion	Long-lived or perennial plants in the farming system, e.g. perennial genotypes of annual crops, perennial species such as forages and trees
High mass production the main target of genotypic and agronomic improvement	High fertiliser input and frequent pest control to support high production, both commonly leading to pollution; harvest of grain and fruit with low nutritional value	More efficient (if lower mass-) production using species and genotypes yielding products of high nutritional quality
Reduced diversity among species and genotypes to comply with dominant supply chains	Potential for widespread disruption due to adverse weather affecting many crops simultaneously, and adaptation and spread of pests due to evolved resistance to agrochemicals	Increase the range of phenology, growth habit and product type coupled with agronomic transitions to crop and grass mixtures (see below)
Limited range of harvested products to suit pre-defined major markets	Agriculture locked-in to supply chains and specific technologies, restricting capacity for change	Generate new multiple uses, supply chains and markets for crop products
B Agronomy		
High sowing and stand density to maximise canopy expansion and resource capture	Benefits in favourable conditions not realised when resources are limiting, e.g. soil stores exhausted early, not replenished by rain or irrigation	Reduce stand density to extend period over which a limited resource is used; combine species able to extract resource from different soil depths or at different time in the yearly cycle
Deep and regular soil cultivation facilitates sowing/weed control and encourages rapid crop growth	Repeated disturbance reduces microbial structures, organic carbon and cohesion of soil; exposure to rain, frost and wind raises potential for erosion of soil, together with loss of fertiliser and pesticide.	Minimum tillage to stabilise soil and build carbon; reduce periods of uncovered soil, e.g. undersowing of main crop near or after harvest with a cover to capture unused nutrients

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Characteristic	Typical problems	Examples of regenerative intervention
Single species crop stands and limited variability in grass mixtures facilitate planning and agronomic operations	Uniformity across the management unit makes crops prone to adverse weather and pests, weeds and disease	Mixtures of genotypes or species to limit susceptibility to weather and biotic stress, e.g. through intercrops and agroforestry
Simplified rotation allows concentration on the most productive, economic crops	Pests take advantage of continuous cropping with the same genotypes, resulting in rising pesticide usage; high-output crops need high annual inputs of fertiliser.	Re-establish greater crop diversity in rotations, especially through legumes that improve soil and leave N-rich residues for the next crop; introduce sown grass leys (temporary areas of pasture) in arable rotations

(Ehrmann & Ritz, 2014; Suter et al., 2015; Raseduzzaman & Jenson, 2017), including cases where herbaceous grasses or crops are grown with trees in an agroforestry system (Leakey, 2012; Ong et al., 2015). Methods of cultivation and harvesting are necessarily modified during early trialling to cope with the new configurations of genotypes and species. Table 1 summarises some of the genotypic traits and agronomic interventions that have developed from modern technology, common problems arising from their adoption and the phenotypic or agronomic changes that can make fields more resilient. Most interventions in Table 1 directly affect the way in which other living organisms mediate ecosystem processes. A greater diversity in crops means more ecosystem processes can be regulated. Specific examples are given in Sections 5–9 on principles and Section 10–11 on practice.

4.3 Creation of a diverse farmland habitat

While the largest area on farms is usually that of managed fields, integrated farming also aims for regeneration or creation of habitats whose function is not directly for production. While habitats such as field margins, hedgerows, copses, tree lines, wildflower meadows and wetlands are not generally a source of saleable product, they have several important functions that still contribute to economic output (Hawes et al., 2021). One function is to contain resources within the field and farm, e.g. to prevent soil and nutrients moving out of fields in surface water flow and possibly being lost into waterways. Another is to provide habitat for beneficial organisms, such as predators that will move into the managed areas of fields and feed on crop pests. A third is to modify the microclimate of the farm, both for the benefit of crops and to shelter livestock,

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for example by protecting animals from the effects of high winds or providing shade from intense sunlight.

Habitat is sometimes also created to aid a wider range of biodiversity, under the category A for B. For this to be effective, farms need to connect across the landscape, creating mosaics and corridors that support rare or endangered species (Topping et al., 2003; Perfecto and Vandermeer, 2017). People are also part of this wider biodiversity. Regeneration at all scales from soil to landscape can reconnect people to their source of food and contribute to their culture and sense of 'place' (Ball et al., 2018).

5 Design principles for integrated farm management: stores and fluxes

This section considers the way management interventions can affect living organisms and the way they in turn regulate ecological processes. The emphasis is at the scale of the field and other productive areas. The units of biodiversity range through species, functional types and communities. Biological diversity at smaller scales of the individual or group of individuals interacting in a 'trait space' is the foundation of all higher scales (Squire, 2020) but is generally too fine to be of practical use in farm management.

In natural ecosystems 'stores' (which hold essential chemicals and energy) and 'fluxes' (the movement of these chemicals and energy across space and time) tend to be balanced. The large global fluxes are those of solar radiation, water, air movement and loss of particles from soil and bedrock. Together they allow plant life to turn carbon dioxide in the air to living matter (Fig. 5). The main stores relevant to this chapter are living matter in plants, microorganisms and invertebrates, soil organic matter, mineral nutrients (such as phosphorus, potassium and nitrogen) and water. The main fluxes pass through the soil-plant system, adding to or taking from the stores (Monteith, 1965, 1972).

Incoming short-wave solar energy is either absorbed, reflected back, contained as thermal energy or emitted from plants and soil as long-wave radiation. The energy content of agricultural vegetation is typically around 1% or less of the solar energy it receives (Monteith 1972; Slattery and Ort, 2015). Turning to another kind of flux, precipitation fills soil with water, is taken up by plants and evaporated back to the atmosphere via transpiration (Hoekstra et al., 2011). Excess water runs off the land as surface flow, drains through the soil to the bedrock or evaporates directly from bare surfaces. The water content of plants is a very small fraction of the water they receive and transpire. In producing one unit of dry matter, plants transpire around 1000 times the mass of water (Brendel, 2021; Hoekstra et al., 2011).

Fluxes, therefore, can be very large compared to the stores, and one of the crucial functions of an ecosystem store is to regulate fluxes. In a perennial

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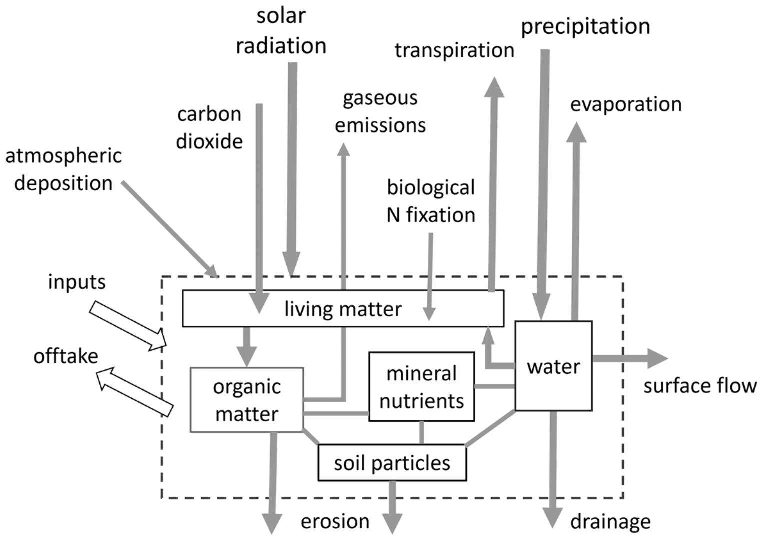

Figure 5 Main stores (in boxes) within the soil-plant system (dashed box), natural fluxes (grey arrows) and indicative human influences (open arrows).

forest or grassland, e.g. high solar radiation is balanced by evaporation of water through vegetation to achieve an equable temperature, and layers of vegetation shield soil from the most intense rain and heat. Stores also allow a system to survive through adversity. In seasonally dry regions, life might wither above ground but, when water returns, the stores re-activate by tapping below-ground resources. If a store is obliterated locally, it can regenerate from neighbouring stores, provided the latter remain in good condition. The capacity of natural systems for survival and regeneration arises through the diversity of their integral life forms. This diversity channels energy and matter through multiple internal pathways and gives the store the capacity to resist and recover from a range of negative external influences.

Agricultural systems are based on the same basic stores and fluxes, but have additional fluxes in the form of human inputs of energy, nutrients and (agri-)toxins, and outputs of harvested crops or livestock. These human-induced fluxes can be large enough to destabilise a system's stores if not carefully regulated. Soil organic matter (SOM), in particular, is crucial to the survival of farming. It influences a soil's capacity to hold water, its penetration by plants and other organisms, and its resistance to erosion. SOM is formed over long periods by micro-organisms processing plant matter and combining the resulting carbon-rich compounds with mineral particles into a complex matrix. However, the burning of vegetation, disturbance by grazing animals, intrusive tillage and application of fertiliser and pesticides reduce the store by detaching carbon compounds from the matrix or encouraging their loss by respiration

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(Grandy and Robertson, 2007). Ultimately, a depleting soil store may feed back negatively to reduce the capacity of land to produce crops or livestock and even, to make agriculture impossible.

Among agricultural land uses, growing arable crops with tillage tends to result in loss of carbon while grass and other perennial vegetation result in more carbon being stored in soil (Soussana et al., 2004; Lemaire et al., 2017). Systems of soil cultivation in which seed is drilled directly into soil (e.g. no tillage, minimum tillage, non-inversion tillage) have resulted in higher soil carbon sequestration than when intrusive, mechanical tillage is used to invert and fragment the soil (Grandy and Robertson, 2007; Takoutsing et al., 2016; Rahmati et al., 2020). However, the effects of various low tillage methods on soil carbon dynamics vary with local conditions and do not always increase soil carbon (Valkama et al., 2020). Even where soil carbon is restored, it may not reach the same equilibrium that it attained before agricultural activity started.

Nitrogen (N) poses a unique set of challenges because of its widespread application as an industrially manufactured fertiliser. Natural sources of nitrogen input to soil are by biological fixation through the symbiosis between soil-living bacteria (rhizobia) and the roots of certain plants, mainly legumes (Jensen and Hauggaard-Neilsen, 2003; Kopje and Nemecek, 2010). By the 1990s, however, inputs of manufactured N-fertiliser came to dominate the nitrogen cycle in agriculture (Evans, 1993; Robertson and Vitousek, 2009; Robertson et al., 2013). N-fertiliser now makes a major contribution to greenhouse gas emissions and hence climate change through the use of fossil fuel in the manufacturing process and then through chemical transformations after it has been applied to fields (Smith et al., 2007; IPCC, 2023). The most effective of post-application greenhouse gases are nitrous oxide, much of which originates from conversion of fertiliser nitrogen in soil, and methane arising from livestock and manures. Nitrogen fertiliser also raises emissions of carbon dioxide from agriculture when the organic matter it generates decays or burns. The fluxes of GHG emissions due to nitrogen fertiliser combined with nitrogen losses to water through surface flow and drainage are responsible for much of the pollution from agriculture (Sutton et al., 2011; Norton and Ouyang, 2019; Walling and Vaneeckhaute, 2020). The other two plant macro-nutrients, phosphorus and potassium, present similar but less severe problems because of lower application rates (and lower plant content of these nutrients) and their greater capacity to bind to soil. A major aim of integrated management is to regulate the nitrogen cycle by minimising loss and maximising uptake by plants.

Stabilising and regenerating agro-ecosystems therefore requires knowledge and quantification of the important stores and fluxes that maintain the system and the organisms that mediate the biophysical processes involved. In order to design integrated systems effectively, it is essential to define the limits and 'safe' ranges in which the organisms, processes and states might

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fluctuate while remaining sustainable for agriculture (Section 6), and then identify and put into practice the 'chains of effect' leading from agronomic interventions through to major outputs (Section 7).

6 Limits and safe ranges

Ideally, a population, process or any biological state can be defined in terms of 'safe limits' within which it can vary without impairing the long-term functioning of the system (Squire, 2017b). In Fig. 6, an attribute varies over time around a mean (the central line) and between two sets of limits. Between X1 and X2, the population or process can operate effectively; in the ranges X2 to Y2 and X1 to Y1, it operates but is impaired in some way; but outside Y1 and Y2 the population declines or the process fails. The asterisks indicate points where the process leaves range X but can be brought back by specific management interventions. The dashed line heading towards and past Y2 represents a point where, because interventions are not applied, the process fails.

Defining the ranges X and Y is straightforward for some but not all factors. For example, the lower limits for biological or chemical contaminants or toxins in feed and food can be defined based on experience and experiment. In contrast, defining limits for many organisms and processes is a major challenge since they depend on multiple interacting environmental and ecological factors. Moreover, the limits for a population or process are rarely absolute, but vary with climate, soil and other aspects of the location, as described below by examples of soil organic carbon and the soil seedbank.

Soil (organic) carbon is one of the major ecosystem stores, produced over long periods by plants sequestering carbon from the atmosphere. It is widely used as an indicator of general soil condition and the capacity of

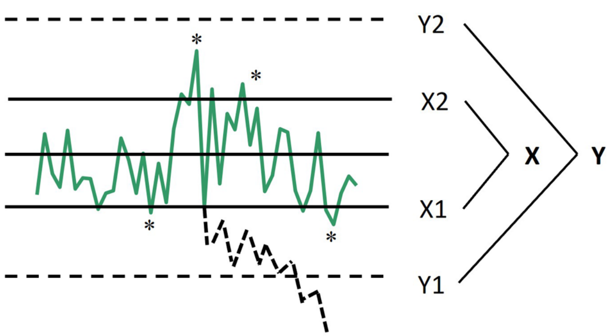

Figure 6 Representation of a population or ecological process varying over time around a mean (central line) and between limits X1 to X2 in which it can operate effectively, and limits Y1 to X1 and X2 to Y2 where it is degrading and needs to be returned to range X by interventions (marked *). Dashed line indicates where a process moves outside X and Y to its permanent damage. Text gives further explanation (adapted from Squire, 2017b).

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land to continue absorbing atmospheric carbon. It is a major constituent of soil organic matter (SOM) which forms the habitat for the soil microbiome and associated invertebrates (Jackson et al., 2017; Rees et al., 2005). Soil carbon is usually quantified as the mass of carbon per unit dry mass of soil (e.g. g kg^{-1}), commonly converted to a percentage (typically 0.5% to 10% for agricultural soils), whereas carbon stocks (estimated to a stated soil depth) are usually given as mass per unit land area (e.g. t ha^{-1}). Soil carbon has been estimated over extensive land surfaces by a combination of ground survey, remote sensing and modelling (Luo et al., 2011; Zhang et al., 2015). Data have been combined from many sources into a Global Soil Organic Carbon Map (FAO, 2018), which shows the location of carbon stocks in different soils, climates, and vegetation types. For example, 33% of the global soil carbon to a depth of 0.3 m is in forests, 30% in savannahs and shrublands and 24% in croplands and grasslands.

The main questions for integrated management concern the range of zone X in Fig. 6 for soil carbon and the scope for regeneration if it moves out of X. Soil carbon influences plant growth through several attributes, including soil bulk density and water-holding capacity. It supports the many organisms that live and feed in soil and in the process make nutrients available to crops (Lal, 2012; Valentine et al., 2012). Soil carbon occurs in a range forms or pools, depending on the type of plant that deposits the carbon. The pools break down or transform at different rates and influence plant–soil interactions in different ways (Blair et al., 2006; Grandy and Robertson, 2007; Rahmati et al., 2020). Its safe ranges for agriculture are difficult to generalise but the lower limit X1 has been approximated at around 2% (Loveland and Webb, 2003). The limit at which yield begins to decline depends, however, on other aspects of soil and agronomy. For agricultural soils in the authors' study area in Atlantic zone Europe, a workable range for X was proposed at between 2% and 5% C but, provided crops were supplied with very high nitrogen fertiliser, cereals yield was still near maximum even at and just below 2% C (Squire et al., 2020, 2023).

A second example of defining limits concerns the buried seed, or soil seedbank, that occurs in arable land, grass pasture and regularly disturbed semi-natural ecosystems (Levin, 1990; Warr et al., 1993; Milberg, 1995). Dormant seeds can regenerate a plant community after the above-ground vegetation has been erased, for example by fire, drought or low temperature. In agricultural systems, the seedbank typically contains some species with properties that are positive for the farmed environment, e.g. by supporting food webs (Norris and Kogan, 2000; Marshall et al., 2003), but others that compete aggressively with crops or are poisonous to people and livestock (Squire, 2017b). Poisonous weeds need to be reduced to near zero, and have been in most developed agriculture by targeted weed control and rigorous seed cleaning. For highly competitive species, experiments and models have

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long been used to define a weed threshold or lower limit of population density at which control is triggered (Cousens, 1987; Walsh et al., 2018).

Limits for the beneficials in arable-grass agriculture have been more difficult to define because of the many plant species and functions they support. For example, soil seedbanks, quantified as number of seeds per unit field surface area to a depth of 0.25 m, in the range 2000–8000 m^{-2} have been proposed as likely to contain a high functional diversity in maritime climates of north-west Europe (Squire, 2017b). Seedbank number itself does not directly equate to emerged weed cover or plant mass, which also depend on field management and competition from the crop. A limit of around 10% ground cover by weeds growing underneath a crop canopy (Smith et al., 2020) is one that would support a diverse above-ground food web without adversely affecting yield. Ground cover has been further quantified in terms of solar radiation flux. A 10% weed cover during the spring-summer period of weed growth intercepted up to 100 MJ m^{-2} (total) solar radiation equivalent to 5% of the 2000 MJ m^{-2} typical for a long-season crop (Squire et al., 2021). This weed cover offered little direct competition with the crop since it resided below the canopy. Therefore the minimum requirements to support beneficial plant species in these climates could be considered to be a seedbank of 2000 m^{-2} coupled with management that regulates emerged species to 10% ground cover during the main phase of growth or 5% of the incoming solar radiation over the life of a crop.

The main challenge is to manage the balance between competitive and beneficial weed species. The practice of *integrated weed management* to regulate this balance, for example through crop rotation, mechanical weed control and highly targeted herbicide application, has been established for some decades (Hatcher and Melander, 2003), but its limited use in high-input cropping has been attributed to farming's lock-in to existing technologies such as chemical control (Swanton and Murphy, 1996; Holst et al., 2007; Baastians et al., 2008).

7 Chains of effect

The crucial role of biodiversity in field-farm management is illustrated by a 'chain of effect'. Its main components are as follows:

1. Management interventions;
2. Living organisms (life forms);
3. Ecological processes; and
4. Higher level outputs or goals.

The definition of the latter can be varied, depending on the nature of the agricultural ecosystem and its role in a society, country or region. For example,

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goals could be defined as ecosystem services (provisioning, supporting, regulating and cultural services), as in the Millenium Ecosystem Assessment (MEA, 2001), or by the four spheres of sustainability – environmental, economic, societal and political (O'Connor, 2006). Or the goals could align with environmental regulations, governing for example the limit of a pollutant that can be lost from a field or farm.

As an example, a furrowed border is constructed around a field and sown with a plant cover (the intervention). Living microbial matter (life form) and decomposing organic matter hold the furrowed soil in place (process), then the sown plants (life form) emerge and cover the ground, reducing fluctuation in temperature and exposure of soil (process). During heavy rain, the furrows hold water and reduce its rate of lateral flow out of the field (process) and so contribute to reducing soil erosion and loss of fertiliser (supporting and regulating ecosystem services).

In another example, a grain legume is sown in rotation with mainly cereal crops (the intervention). Bacteria in the soil invade the legume's roots to form nodules (life forms). The nodules fix atmospheric nitrogen (process), leading to flows of nitrogen from air to soil (process) and the fixed nitrogen lowers the need to apply mineral nitrogen, thereby supporting crop yield (provisioning) and reducing GHG emissions on the farm (regulating).

While a chain of effect can be used to examine the way to achieve all high-level goals at field and farm scales, it is rarely simple or linear, leading from one intervention to one goal. Rather, a chain branches, one intervention affecting other interventions and on to a range of organisms and processes and in turn several higher goals (Squire and Iannetta, 2018). Examples of more complex chains are given in Fig. 7. Four types of intervention (crop choice, fertiliser, pesticide and tillage) influence life forms (crop, wild plants, invertebrates and soil microorganisms) which, in turn, feed through four sets of processes (resource capture, soil N dynamics, soil organic matter store and soil structural cohesion). The high-level outcomes are expressed in terms of ecosystem services represented by yield (1. provisioning), soil condition (2. supporting), reducing loss and pollution (3. regulating) and wildlife in the form of A for B (4. cultural, aesthetic).

Looking at the chain of effect in Fig. 7, a high-input winter cereal (Fig. 7a) has mainly negative influences on life forms, operating through herbicide (H), insecticide (I) and fungicide (F), fertiliser (especially high nitrogen application to ensure high yield and protein quality) and intrusive tillage. It produces a valuable grain crop but has mainly negative effects on the other processes and services. In contrast, a diverse grass-legume mix for livestock forage or hay (Fig. 7b) has positive influences on the other life forms. Among other benefits, it provides a continuous leaf canopy to protect soil from solar income and rain. Reduced tillage encourages fungal networks to form in soil. The legume

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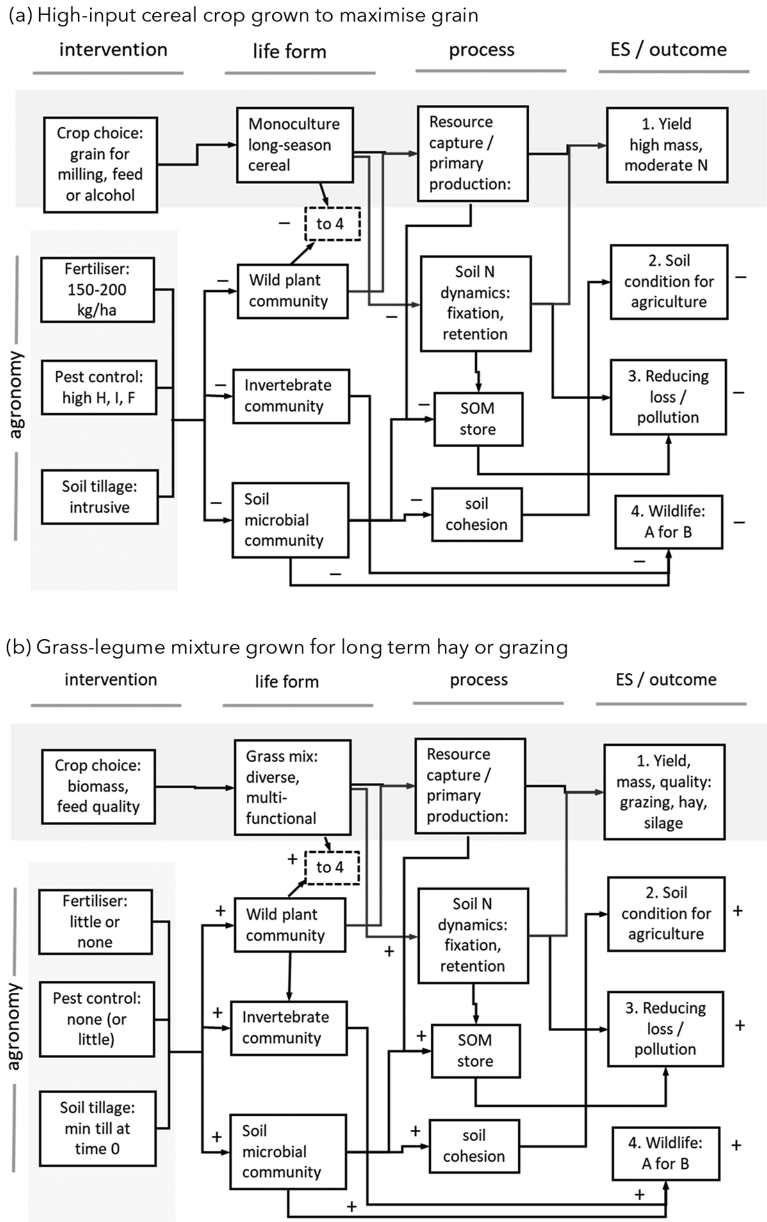

Figure 7 Simplified chain of effect from crop choice and three other interventions to indicative high-level goals (1 = provisioning, 2 = supporting, 3 = regulating, 4 = cultural) for (a) a high-input cereal crop grown to maximise grain yield, and (b) a grass-legume mixture grown for long-term hay or grazing. Plus or minus signs show the direction of effect leading to 2, 3 and 4. Pesticide inputs: H, herbicide; I, insecticide; F, fungicide. The text gives further explanation.

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component fixes atmospheric nitrogen, thereby reducing fertiliser input. Together the enhanced, in-field communities also support A for B, for example by providing wildlife habitat.

Chains of the type summarised in Fig. 7 can be extended to include future use of the product. For example, the mixed sward is likely to be used to feed livestock, which then initiates a further chain leading to economic returns from livestock sales, to use of livestock manure as fertiliser and to negative effects through greenhouse gas emissions and water pollution. The complexity of within-farm chains and the trade-offs between positive and negative are increasingly examined through whole-life-cycle analysis and multi-attribute decision support tools (described in Section 10).

The crucial step in defining a chain of effect is to understand the capacity of the life forms, first to be affected by management interventions (functional response), and then to influence an ecological process (functional effect). These types of functions are well known from studies of natural ecosystems but are rarely acknowledged in agriculture. The emphasis on much agricultural science in recent decades has been on the crops, their genetics and to a lesser degree their physiology (Azam Ali, 2021). Knowledge of the functional properties of microbes, other plants and invertebrates is often lacking and hinders regenerative practices, as recognised in FAO's major treatise on global agricultural biodiversity (FAO, 2019). Science and management can in principle work together to provide and apply such information, but appropriate research funding is commonly insufficient.

As described in Section 4, indigenous and traditional knowledge can be valuable today as a guide to transitioning towards diverse, integrative agriculture. Written records of practices long forgotten may also provide guidance to regeneration. An example is offered by the complex 'grass' mixtures constructed throughout the 1800s for different purposes in Europe (Stephens, 1841; Stebler & Schroter,1889; Elliot, 1898). Four of such seed mixtures (Fig. 8) show an increasing number and diversity from short-term hay to long-term grazing. Species of grasses, legumes and other dicotyledonous plants were combined to match their botanical functionality with the local conditions and intended use or products. Number of species ranged from 2 grass and 2 legume in a 1- to 2-year hay mixture to 9 grass, 4 legume and 4 other dicot (17 total) in a mix for long-term grazing. Traits considered when constructing the mixes included inter-species compatibility, speed of canopy formation, ground coverage, height of sward, nutritional quality for livestock, balance of leaf and seed, availability to livestock through the year, ability to penetrate plough-pans and, finally, the capacity to transition from a short-lived to a long-lived perennial state as the sward aged.

In that period, practitioners perfected their seed mixtures by extensive trialling and experience. They did not know, for example, the mechanism by

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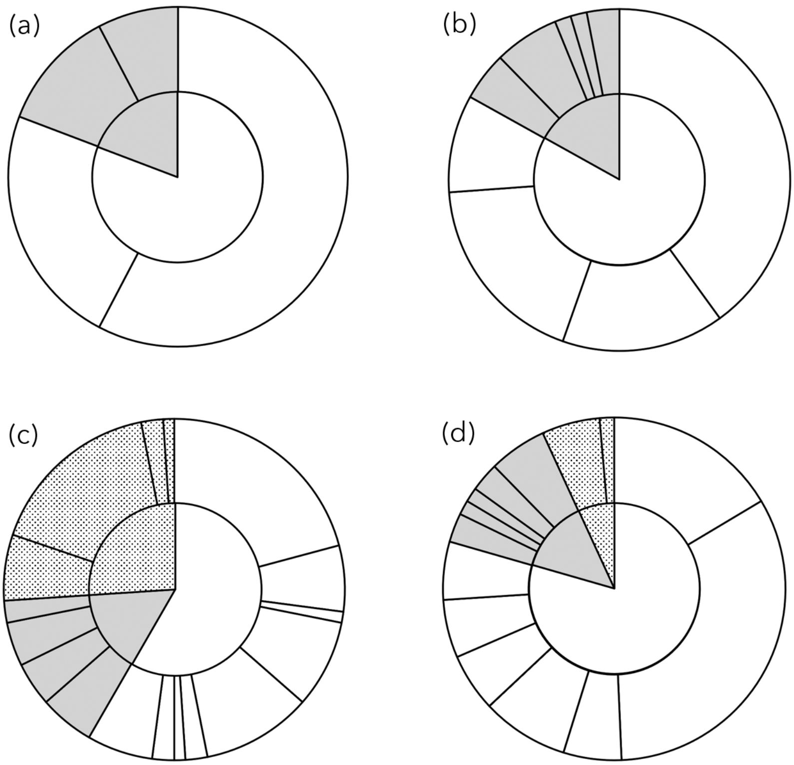

Figure 8 Sown seed mixtures developed in the 1800s in Europe for (a, b) hay or grazing for 2 years, (c, d) long-term grazing, showing in inner circle, proportions by seed weight in the sown mix of grasses (unshaded), legumes (grey), and other dicots (pattern); and in outer circle the proportions of individual species of each type. From data summarised by Findley (1925) based on earlier trials.

which legume species fixed atmospheric nitrogen, but knew from experience that, if grain or forage legumes were grown in a rotation or a mixture, they were nutritionally enriching for the other species. Their approaches and methods would likely have defined a chain of effect as in Fig. 7. Each species or variety opened a new channel or reinforced an existing one. This work provides an example that can be followed today to regenerate degraded land.

The simplified chains in Fig. 7 show that the major aims of field and farm management can rarely, if ever, be achieved by changing just one characteristic of the crop or the agronomy. Rather, a set of interventions needs to be introduced to regulate the various ecological processes that combine to deliver intended outcomes. Given uncertainty in the state of the weather or the presence of beneficial organisms, several interventions may be needed to cover even a single process.

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Figure 9 Contrasting fields of tea in Sri Lanka: left, soil eroding, crop failed, land exhausted; right, soil conserved, tiered canopy including N-fixing trees, crop sustainable. Photographs by G. R. Squire, 1989.

A more recent example of applying multiple interventions is given for a perennial crop, tea (*Camellia sinensis*) in Fig. 9. Two fields had been planted on a similar slope in the same climate. The field on the left with bare, eroding soil and poor growth of the tea, has passed through sustainable limits and is transitioning from extractive production (Fig. 1, box 4) to exhaustion (box 5). The field on the right received multiple interventions to keep it in sustainable production (box 3): each row of bushes is contoured to limit downward flow of water, soil is mulched (not visible), and leguminous perennials are planted to fix nitrogen, build soil carbon and form a multi-tiered canopy which gives shade and reduces rainfall impact.

The deployment of multiple changes in crop and management has been termed a 'portfolio approach' to farm management (Robertson and Vitousek, 2009). An example of the approach is now given for the regulation of nitrogen in crop and grass production.

8 Portfolio approaches to crop management: the example of nitrogen

Nitrogen (N) is essential for growth and yield of crops and grass (Cui et al., 2014). Mineral N applied as fertiliser is a major pollutant of water (Ascott et al., 2017; Azevedo et al., 2015) and (as nitrous oxide) makes a major contribution to GHG emissions from cropped land (Norton and Ouyang, 2019; Robertson and Vitousek, 2009). Compared to many other indicators, the processes that determine its stores, flows and losses have been well researched. Management of N therefore provides an instructive example of the potential of regenerative practice based on science (Norton and Ouyang, 2019; Whetton et al., 2022).

N input as fertiliser is primarily determined by economic return based on the N-content of the crop or grass in question. Its limits for environmental safety are more difficult to assess. To reduce waste and environmental damage,

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the excess should be zero, i.e. uptake should equal application. Whether an acceptable limit higher than zero can be set (i.e. some waste allowed) then depends on the effect of the nitrogen on biodiversity and habitats, both in and outside the field or farm. In Europe, certain areas or parts of catchments were designated through the EU Nitrates Directive as Nitrate Vulnerable Zones (NVZs) in which farming had to abide by certain rules to limit the application of fertiliser (Van Grinsven et al., 2012).

The designation of NVZs implies that less stringent practice was permissible outside the zones, but there is widespread agreement that agriculture should act to minimise the loss of nitrogen from fields. However, management that relies only on N input being matched by the crop's expected uptake will rarely achieve zero waste. The process of nitrification, which converts nitrogen compounds to nitrate ions, provides plants with a readily accessible source of N, but one which is also highly mobile and readily lost. Losses are especially large during years in which the weather after nitrogen application limits plant growth and hence capacity for N uptake. In a study of the N-balance in European cropping (Leip et al., 2014), the applied nitrogen lost as waste and pollution amounted to around half the nitrogen applied.

To account for uncertainties in the weather and a crop's performance, a 'portfolio approach' to nitrogen management has been recommended to ensure most nitrogen is taken up by crops or retained in soil (Robertson and Vitousek, 2009; Subbarao et al., 2013; Whetton et al., 2022). A portfolio approach consists of a range of interventions applied to a field and any associated livestock, both during a growing season and over longer periods. A portfolio, rather than a single action, is needed because nitrogen uptake, retention and loss are complex processes influenced by many factors (Norton and Ouyang, 2019), whose relative importance in any cropping cycle will be uncertain. Targets of a portfolio approach are shown in Fig. 10 in relation to the main channels for input, offtake, excess, loss and retention of nitrogen. Examples of specific interventions are listed in Table 2, with an indication of the organisms involved (B for A).

Two forms of B for A recur throughout Table 2: the presence of legumes that fix their own N and bring general benefits for soils and food webs (Jensen & Hauggaard-Neilsen, 2003; Kopje & Nemecek, 2010; Iannetta et al., 2016; Stagnari et al., 2017; De Notaris et al., 2021); and the use of mixtures of species and functional types that open and regulate many more ecological processes than can be activated in mono-cultures (Ehrmann & Ritz, 2014; Suter et al., 2015; Kaye and Quemada, 2017; Raseduzzaman and Jenson, 2017).

However, not all interventions in the portfolio are well understood or widely applied. One such is the use of nitrification inhibitors that slow the release of mobile nitrate. Some inhibitors are released, for example as root exudates, by

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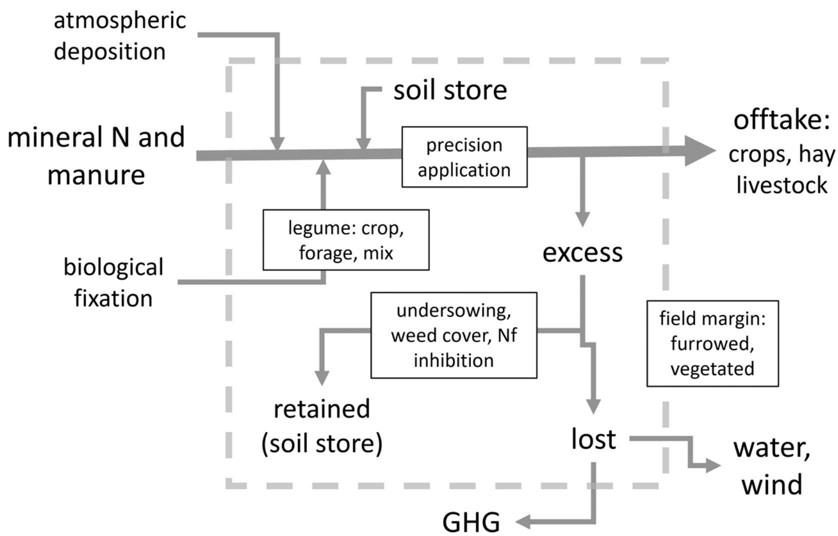

Figure 10 Nitrogen movement and retention in fields, simplified to show main interventions (boxes) in a portfolio approach to minimising N inputs and losses and maximising efficiency of offtake. Text gives information on the interventions. Nf is nitrification.

certain crops and wild plant species (Subbarao et al., 2013; Wang et al, 2021). Others are manufactured chemicals that can be applied to crops or pastures (Moir et al., 2007; Hargreaves et al., 2021). Moreover, the effectiveness of some interventions is uncertain and may vary with context: for example, the application of crop residues to soil may have a range of positive and negative influences (Abalos et al., 2022).

The portfolio approach to the management of nitrogen is a prime example of the need for integration – of crop types, agronomy, sequence, microbiome, food webs – to achieve a result that is simply not possible through any single approach. The use of interventions to achieve multiple aims, to open multiple channels, is commonly more readily adopted by low-input agriculture. Figure 11 shows examples from low-input but highly developed cropping systems that apply legumes, cover crops and mixtures. The latter includes legumes and other species in various configurations, and also perennials for their benefits to soil carbon building and regulating the microclimate.

In contrast, in many regions where intensive and extractive agriculture is the norm, the complexities of low nitrification management coupled with a lock-in to existing technology can result in resistance to change, as shown by the low adoption of legumes in some regions, despite their known benefits

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Table 2 Agronomic interventions contributing to a portfolio approach to nitrogen management through the action of living organisms (B for A).

Intervention	B for A
Balancing fertiliser N with crop requirement and measured soil N through precision agriculture	Crop phenology matching soil N availability
Nitrogen-fixing grains and forages that require no or little N application yet increase soil N, available for the next crop.	Bacteria (rhizobia) in soil able to form N-fixing nodules on legume roots
Nitrogen-demanding species or mixed covers and catch crops sown to take up excess N, for example following a cereal	Additional sown species differing from crop in phenology and N-requirement
Use of crop or grass mixtures, including those with legumes, as sown mixed seed, row intercrops or tree-crop systems	Multiple crop species filling more of the trait space and opening more channels
Diverse, naturally regenerated weed understoreys that scavenge excess N in areas and at times where crop N uptake is low and leave high-N organic matter	Non-crop plants, originating in the soil seedbank, enhancing above- and below-ground food webs
Nitrification inhibitors released by certain plants, or applied in chemical form, to limit the rate at which nitrogen compounds are converted to mobile nitrate	Certain crops and wild plant species whose exudates inhibit nitrification in soil
Diverse field margin vegetation designed to trap N in surface water flow, and that can be cut and returned in composted form to the field	Multi-species seed mixes sown outside the cropped area
Low disturbance of soil (no or minimum tillage)	Fungal networks improving soil cohesion, carbon content and nutrient retention
Transfer of livestock manures and crop-grass residues between fields to match need for nutrients	Microbial processes in livestock and soil decomposing plant matter to release nutrients

(Magrini et al., 2016). A widespread transition to legumes and low-nitrification management might well need a redirection of government support and incentives to overcome these barriers to change (Gu et al., 2021).

The outputs from mixed cropping, especially when compared to sole cropping, should not simply be quantified by dry mass per unit field area. Several options exist, including the area of land or period of time that would be needed to reproduce the output of the mixed crops if each component was grown alone (Willey, 1985; Azam Ali and Squire, 2004). Generally, mixed crops use area more efficiently because they interact positively with each other and use different 'fractions' or 'pools' of soil resources. The grass seed mixtures developed in 1800s in Fig. 8 were thought to bring benefit 'because of the interlacing' (Findley, 1925) – the ability of roots of different species to occupy the same soil without competing.

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Figure 11 Mixed cropping in Myanmar (Burma): (top left clockwise) groundnut-maize intercrop; rows of sunflower in chickpea field (inset, chickpea pods); multi-species row cropping including two perennials, cotton and pigeon pea (insets, cotton bolls and pea pods); three-species mixed crop, plants withered in dry season, taro, *Colocasia esculenta*, still in soil (inset, tuber in hand), the others already harvested, *Capsicum* sp. (inset, chilli drying) and ginger (not shown). The first three examples contain a legume. Photographs by G. R. Squire, 2014.

9 Considerations of area

The different parts of a farm are linked through the movement of resources between them. Resources such as fertiliser, fuel and seed move into the farm from outside, then agricultural products and waste move out of the farm. The balance of resources into, within and out of the farm have changed through the history of agriculture and differ between its existing forms. Many instances of degradation from Fig. 1 boxes 3–4 and 5 have occurred because the balance is swayed one way or another, as shown in the following examples.

In many early forms of agriculture, and in much current subsistence farming, cultivation and nutrient enrichment were concentrated in small productive areas, supported by a much larger area where nutrients were collected as cut vegetation or manure from livestock grazing there. This internal transfer ensured that at least some harvest was possible, but it relied on the supporting area being rich enough in plant growth and nutrients. Another example is shifting cultivation, described in Section 2, where forest or grassland is burned to return nutrients to the soil, on which crops such as maize and upland rice are then grown (Norman et al., 1984; Anderson, 1993). The harvest may constitute food

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for the family or contribute to feeding livestock confined to small paddocks. The nutrients in the burnt areas are exhausted after several years, the land is abandoned to revert to a secondary forest and the procedure is repeated in another area of land. In both these cases, limiting nutrients means that adequate provision of food requires large areas of land per unit population. A rising human population density, exacerbated by climatic extremes and wildfires, means less land available for such agricultural practices.

In comparison, the perceived success of high-intensity farming arose from its capacity to increase output per unit area through development of new, high-yielding crop varieties, use of manufactured or mined fertiliser, modern irrigation techniques, mechanised cultivation and agrochemical pest control. In those global regions that could afford the inputs (Azam Ali and Squire, 2004), farming dispensed with the need to scavenge nutrients over a wide area. Between 1960 and 1990, yield per unit field area typically increased 2- to 3-fold. Estimated globally, a five-fold rise in nitrogen fertiliser usage over this period supported a doubling of the human population on a stable agricultural land area (Kawashima et al., 1997). Since 1990, the population has continued to rise while the area of agricultural land has hardly changed, reducing the area of agricultural land per person by 30% to 0.6 ha in 2019 (FAO, 2021). The rise in output per unit area after the 1950s was indeed a major achievement (Keating et al., 2014), but the rising trajectory of yield levelled in many places after the 1990s (Calderini and Slafer, 1998), while 'yield gaps' between actual and potential production remain commonplace (Tittonell and Giller, 2013; Squire, 2017a; Neumann et al., 2022) and farm outflows have continued to cause environmental harm.

A more extreme imbalance in the cycling of resources occurs where one part of the holding supports livestock under cover for all or part of the year. The livestock is fed both from major inflows to the farm, in the form of feed grown and manufactured elsewhere, and cereal grain or hay grown on the farm. Cycling occurs when the livestock manure is spread onto fields to provide nutrients for the next crops. In principle, this cycling can be highly efficient (Lemaire et al., 2017), but excessive flow from livestock enclosures can lead to serious pollution. For example, manure cycled from high-intensity poultry or beef may be so great in quantity that the land is unable to contain it, resulting in excessive outflow and pollution (Jarvie et al., 2003; Post et al., 2020; Rothwell et al., 2020).

The challenge for integrated farm management is to manage land such that internal cycling is maximised, inflows are minimised and outflows tightly regulated. Farming systems can adapt to ensure cycling of energy and matter between years, fields and farms and between crop and livestock enterprises (Pearson and Ison, 1997; Watson et al., 2002; Lemaire et al., 2017). However, the success of integrated management must be gauged by different or at least

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additional criteria to those such as mass output per unit area which are used to assess high-input farming. Examples include the proportion of land used to grow food, as distinct from other products such as feed and alcohol, metrics on the nutritional content rather than just the mass of food, and the degree to which outflows are causing environmental harm.

The main long-term issues that have to be faced are the declining land area per unit of population and the depletion of soil resources (FAO, 2015, 2021; Hanjra et al., 2017). In principle, soil can be regenerated over long time periods and much of the nitrogen can be provided through biological fixation (and see the case study in Section 11) but, to maintain or improve output where nutrients have been severely depleted, agriculture will have to rely on manufactured and mined plant nutrients, especially phosphate, potash and sulphur.

Integrated management at the scale of the field and farm is unable by itself to meet such future challenges. This is particularly the case in tropical subsistence agriculture where large yield gaps exist between the actual and a defined potential (Squire, 2017a). Tittonell and Giller (2013) in a paper headed 'When yield gaps are poverty traps' have quantified the large gaps in a region of subsistence agriculture between the typical farms and those in the same climate that are well supplied with nutrients. No amount of genetic improvement in crop varieties will close these gaps. It is plant nutrients that are needed. Integrated farm management can contribute, but the global agri-food system has to change drastically to reduce waste of soil, nutrients, crops and food and to recycle on both local and global scales the main plant nutrients before they dissipate to the oceans and atmosphere. The design and implementation of integrated management should therefore be seen as but one practical step towards sustaining future human populations and limiting further environmental damage.

10 Design and implementation of restored farm management systems

This penultimate part of the chapter examines stages in the design and implementation of a system of farm management that both restores biodiversity for agriculture and ensures biodiversity works for the farm.

Restoration occurs in three overlapping phases, beginning with setting the context (Fig. 12 left), followed by quantification of the possibilities given the local topography, climate and infrastructure (Fig. 12 centre) and then implementation of new systems on the farm and the creation of new supply chains (Fig. 12 right).

10.1 Align with global frameworks

The Society for Ecological Restoration (SER) released the second edition of its International Principles and Standards in 2019 (Gann et al., 2019). Several

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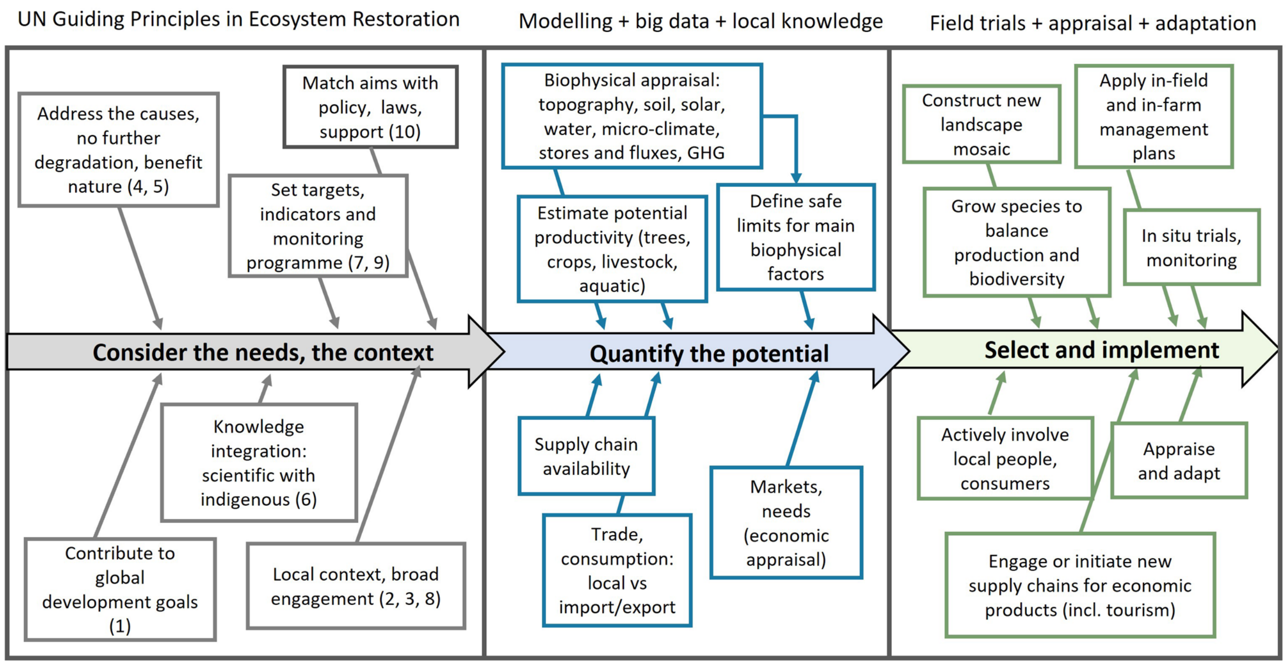

Figure 12 Generalised scheme to guide regeneration of agricultural ecosystems: left-hand panel is based on the UN's Guiding Principles, indicated by numbers in the boxes; central panel compares potential states and options for regeneration; right-hand panel lists activities necessary to put regeneration into practice.

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organisations within the UN, working with SER, published the UN's Principles for Ecosystem Restoration in 2021 to coincide with the beginning of the UN Decade of Ecosystem Restoration 2021–2030 (FAO, IUCN, CEM & SER, 2021). Both sets of guidelines are targeted primarily at restoring degraded natural ecosystems, but they can be used to guide regeneration of agricultural systems.

SER summarises its recommendations in eight categories, the UN in ten, but they have similarities. Restoration in any locality should see itself as contributing to global issues through bringing benefits such as carbon capture and reversing biodiversity loss. Planning and implementation should be inclusive of people and combine different types of knowledge, including indigenous knowledge where it exists. Restoration should benefit biodiversity and ecosystem processes but also people and societies. Restoration in any locality should begin by understanding the causes of degradation and preventing them from doing further harm. An implementation plan should include a baseline (the damaged current state) and defined steps in the progression towards a restored state. Monitoring the transition should be aided by measurable biophysical and socio-economic indicators.

The SER approach recommends that 'native reference systems' are identified as an aim. Such systems might be examples of undamaged habitats in the same or similar environment. When the guidelines are applied to agricultural ecosystems, the reference might be a type of farm or production system that has provided sustained output for centuries or millennia (see Section 2). SER is also more specific in recommending that restoration projects work with the capacity of microbes, flora and fauna to revive themselves after damage and that different projects should work together to maximise both local and landscape-scale biodiversity. In an agricultural system, each farm will need to regenerate and sustain its soil microbiome and microfauna, then contribute with other farms to a landscape that regulates water flows, reduces erosion and provides habitat for wildlife (Perfecto and Vandermeer, 2017).

Crucially, 'Policy Integration' is the last of the UN's 10 Principles. Restoration – to be effective – needs to be supported by political will and effective governance that together provide the right incentives. The degradation of farmed ecosystems that has occurred over decades and centuries cannot be reversed in a few years.

In a scheme used here for restoring biodiversity, the UN's 10 Guiding principles are adapted to define the needs and context for regeneration Fig. 12, left panel), including:

- the organisations and people involved in the regeneration scheme;
- the habitats, species and functional life forms that have been degraded;
- the causes of degradation, the means to stop it and possibilities for regeneration;

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- targets for regeneration (the reference systems) and a plan for monitoring; and
- scope for alignment with policy and support in respect to land being used for agriculture.

The second phase directs attention to the management units on the farm and what in principle can be achieved (Fig. 12, centre). In many regions of the world, research organisations and farming can work together to quantify this potential in terms of:

- the main stores and flows of energy and matter;
- the different forms of agriculture that the land and climate can support, their potential productivity and required inputs, and the wider biodiversity (A for B) they can support;
- target states and safe ranges for the main indicators;
- the capacity of different plant types to generate multiple outputs (channels);
- supply chains and markets consistent with the regeneration scheme; and
- implications for community and employment.

The third phase (Fig. 12, right) begins the transition to a regenerated system. It tests the organisms that will together regenerate stores and sustain the various outputs. Decisions are made on the biodiversity that sustains agriculture (B for A) and the biodiversity that the transition might aim to support (A for B). This phase can continue for many years as methods are adapted based on the results of trialling and monitoring:

- construction of landscape parcels and connectivity, aiming to balance the internal cycling of materials and minimise external flows;
- trialling new systems, e.g. mixed crops, rotations, agroforestry;
- linking with local communities – food cooperatives, local consumption, short food chains; and
- developing new supply chains.

10.2 Decision tools

The processes involved in moving through the stages in Fig. 12, and the outcomes to the right-hand side, can be facilitated by some form of decision-support system that enables the many possible outcomes to be compared. The main choices have to be made in the central part of Fig. 12. Several tools can be applied to part-quantify potential outcomes, among which multi-attribute decision models (MADM) have become widely used. MADMs or decision trees in various forms are constructed as a hierarchy, the attributes at one level combining to define the attributes at the next higher level, and so on.

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Fig. 13 shows an example of some of the attributes whose combined effect is to minimise N losses to water. This branch would be part of a much larger tree.

To the left, boxes with dashed margins show agronomic interventions, whereas boxes with continuous margins show life forms. Each of the latter is the result of previous conditions or choices. The state of the soil microbiome determines whether symbiotic rhizobia exist, and the choice of crop and its performance in the field determines whether symbiosis will happen to allow nitrogen fixation that can replace mineral fertiliser nitrogen. Treatment of the soil and vegetation at the previous harvest combined with activity during the current crop will determine the availability of N in organic residues; then fixation and breakdown will combine to determine how much additional N is needed to satisfy the target crop yield.

Further down, the weed community and field margin vegetation combine with crop growth to give the crop-weed assemblage which, with additional input from tillage, determines the extent of lateral water flow that might move N (and soil and pesticide) out of the field. At this point, as an example, soil organic matter and hence soil cohesion enter the chain from another part of the tree (indicated by an oval rather than a rectangle) to determine surface runoff. Finally, runoff and requirement combine to determine the likelihood of N loss in water moving out of the field. The tree represents a 'chain of effect' linking

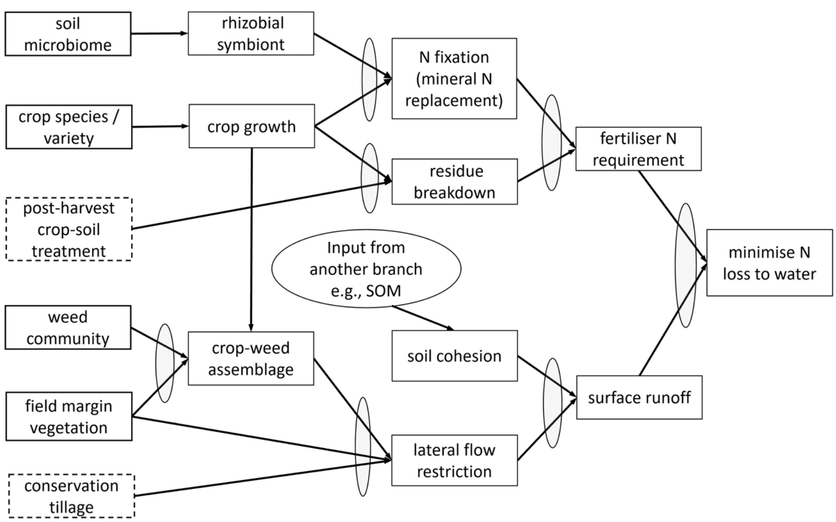

Figure 13 Example of part of a decision tree enabling system planners to evaluate interventions that minimise loss of nitrogen (and other pollutants) to water. The boxes show 'attributes' which can be defined quantitatively or semi-quantitatively, while the vertical ovals show 'utility functions' by which the values of two or more attributes can be combined in DEXi software to determine the value of a dependent attribute. (SOM is soil organic matter, text and Fig. 14 give more information).

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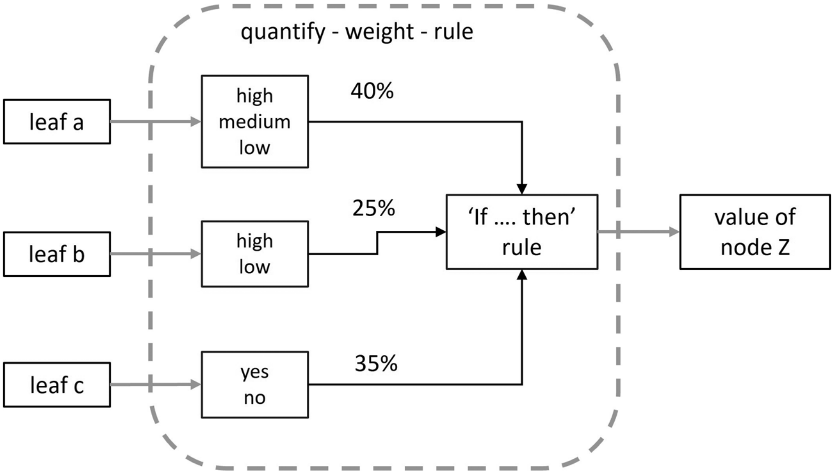

Figure 14 Quantifying attributes in a DEXi model: three attributes (leaves a, b and c) determine the state of a fourth attribute (node, Z) in three steps: the leaf attributes are defined semi-quantitatively (e.g. high/medium/low or yes/no), their contribution to Z is weighted (as %), then conditional (if …. then) rules determine how the values and weightings of a, b and c result in the value of *Z*. Text gives examples.

interventions, organisms, ecosystem processes (states, fluxes), and finally the aim of minimising loss to water. A branch such as in Fig. 13 can be constructed for each of the major high-level outcomes, including GHG emissions targets, food and feed quality and overall soil condition. All branches can then be combined into a single MADM.

A tree of this form is commonly organised using DEXi software (Bohanec, 2014; Bohanec and Znidarsic, 2013). The procedure by which 'lower' (leftward in Fig. 13) attributes are combined to determine the value of 'higher' dependent (rightward) attributes is demonstrated in Fig. 14, where (to continue the analogy of branch and tree) three attributes, named 'leaves' a, b and c, combine to determine the value of a dependent attribute or 'node' *Z*. In an agricultural context, not all attributes are quantified to the same degree: some may be highly quantifiable by measurements or models; others can only be roughly categorised into, for example, high, medium or low states, or bands 1 to 5; and still others may be largely unquantified and regarded as desirable or not (good/bad or yes/no). DEXi models accept such inconsistent classification. First, each leaf is given a semi-quantitative value, then a weighting as to its importance in determining the state of the node; then a set of conditional (if…. then) rules are applied to define the state of *Z* from a, b and c. Functions of this type link all attributes in a tree: if a single leaf value or weighting is changed, there could be ramifications throughout the whole tree.

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A simple example of an 'if … then' rule from Fig. 13 would be – if 'rhizobial symbiont present = yes' and 'cereal crop = yes', then 'N fixation = 0'. Greater complexity could be introduced if the crop is a legume, when there would then be a range of 'if …. then' rules depending on the known N-fixing capacity for different legumes and rhizobial types. In another example, lateral flow restriction might be quantified in terms of high, medium or low. It would be high if field margin vegetation and conservation tillage were both present, low if both absent and medium if only one were present. If field margin vegetation was weighted much more than conservation tillage, then field margins alone might be medium but conservation tillage alone would be low.

Examples of MADM are available for soil condition (Bohanec et al., 2007; Griffiths et al., 2010), assessment of agricultural sustainability (Sadok et al., 2009; Pelzer et al., 2012), and a comparison of conventional and agroecological cropping systems (Hawes et al., 2019; Soule et al., 2023). MADMs in DEXi do not rely on prior expertise in modelling. The tree and utility functions can be constructed, trialled and modified as necessary by a range of stakeholders attending a round-table or online conversation. For example, Colomb et al. (2013) described a procedure for evaluating stockless organic farming using DEXi software to bring together the results of numerous consultations with different stakeholders.

11 Case study: Centre for Sustainable Cropping (UK)

A 'portfolio approach' to managing biodiversity for agriculture was established at the Centre for Sustainable Cropping (CSC), a long-term experiment at the James Hutton Institute's research farm near Dundee, UK, based in the lowland, arable-grass agricultural region of Scotland. The experiment began in 2009 with the aim to develop, implement, test and demonstrate a framework for designing integrated arable cropping systems (Hawes et al., 2016, 2019). The CSC contributes to a coordinated effort in regenerative farming that began much earlier and extends to a wide range of agricultural systems.

Agriculture began here over 5000 years ago when land was cleared of post-glacial vegetation to support species of crops and livestock, most of which originated in Europe and western Asia. Little is known of the state of land and its management until the monastic expansion of the 1100s recorded many instances of poor yield and degraded soil. The monasteries introduced regenerative practices such as soil drainage, weed control and rotation. They recommended growing legumes to improve soil fertility, even though their ability to fix atmospheric nitrogen was not discovered scientifically until many centuries later. A phase of further improvement in the late 1700s and the 1800s again reported degradation and methods to restore soil and boost output but, despite many improvements, agriculture in the early twentieth century

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was unable to provide food security and adequate nutrition for the population (Boyd Orr, 1943).

An Agriculture Expansion Programme, initiated by the government in the 1940s, led to increased output from 1950 to 1990, supported by higher fertiliser and pesticide usage, deeper soil cultivation and improved crop and grass varieties (Squire, 2017b). The lowland landscape remained diverse and output from cereal crops, for example, was high by global standards (Fig. 15, upper). However, the rise in grain output levelled in the 1990s, while fertiliser, pesticide and intrusive tillage continued to damage many fields and cause wider environmental harm, including nitrate pollution (Squire et al., 2022) and soil erosion (Benaud et al., 2020). Over the next three decades, agricultural policy and management maintained yield but failed to achieve substantial reductions in fertiliser usage and greenhouse gas emissions (CCC, 2020), to halt declines in biodiversity, both B for A and A for B (RSPB, 2018) and to provide adequate nutrition for the population (Ritchie, 2017).

Over 5000 years therefore, the agricultural land in the lowland regions of Scotland had moved through repeated cycles of degradation and regeneration, but had not been permanently exhausted or desertified. It was still productive but had reached a point where its negative effects on pollution and biodiversity needed to cease. Non-governmental organisations took the

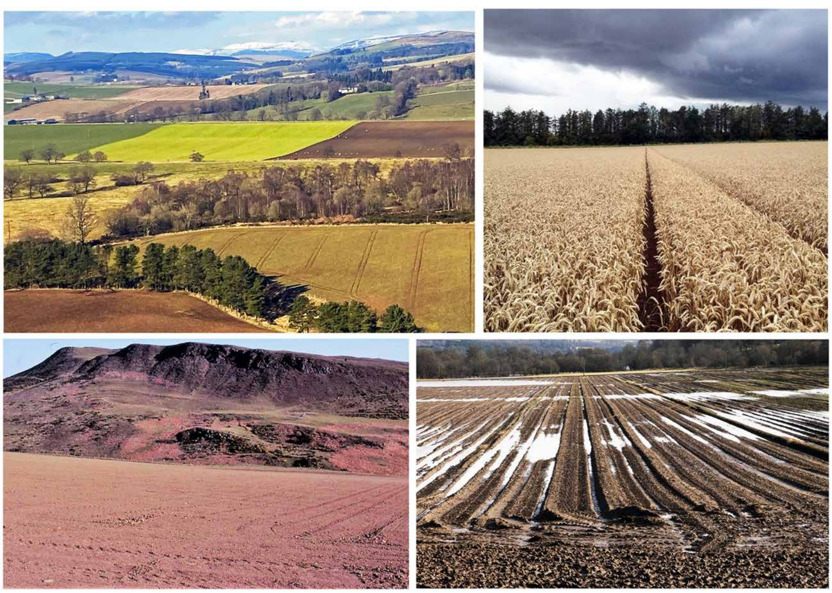

Figure 15 Agricultural land in lowland east Scotland: (top left clockwise) typical diverse arable-grass land use of the region; high yielding cereal; field where the soil is compacted and waterlogged due to intrusive tillage and heavy traffic; a large area of bare soil prone to erosion.

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lead in demonstrating that progress towards regenerating soil and reducing pollution was possible by integrated (Linking Environment and Farming, 2024) or organic (Soil Association, 2024) farm management. Research showed that spatial and temporal integration between grass, crop and livestock in organic systems could be achieved by rotation, including grass leys (temporary pastures) in arable sequences, legumes to fix nitrogen and the cycling of nutrients within the farm in the form of manures and crop residues (Watson et al. 2002). New assessment methodologies were trialled, e.g. to standardise rapid, on-site assessment of soil quality (Ball et al., 2007). A baseline was established through a major regional biophysical appraisal of current farming (central panel of Fig. 12) covering high-input, integrated and organic farming systems. The study confirmed that many attributes of field and farm, including soil condition/health, plant diversity and food webs, were being degraded by high-intensity (mostly arable) management, but could be restored by suitable interventions (Hawes et al., 2010; Valentine et al., 2012; Squire et al., 2020).

Several experimental platforms were established, covering hill farming, mixed livestock and crops. The Centre for Sustainable Cropping (CSC) targeted a high-input system based on cereals for grain. This system was the most damaging to soil in current crop-grass farming and was proving difficult to change. The overall aims of the CSC were:

- to maintain crop yields at comparable levels to those in conventional practice, but with less reliance on non-renewable inputs including fuel, crop protection chemicals and mineral fertilisers;
- to increase the efficiency with which inputs are used, thereby minimising pollution and losses from fields (soil, agrochemicals, greenhouse gas emissions); and
- to achieve these objectives by enhancing in-field and field-margin biodiversity.

The phase of 'select and implement' in the right-hand panel of Fig. 12 began with construction of the CSC platform in which an integrated approach comprising a portfolio of interventions was compared with existing, high-input management. The platform consists of six arable fields covering 42 ha in a rotation of autumn-sown wheat, barley and oilseed rape, and spring-sown field beans, barley and potato. Each field is divided into two halves with the integrated, regenerative system randomly allocated to one half at the outset and then maintained in the same location across multiple crop rotations to detect long-term trends in system properties (Hawes et al., 2019). Fields are monitored annually across a grid of 350 permanent sample locations. The performance of grain legumes was considered the most uncertain. The area sown with peas and beans in the region had declined since the 1850s, reaching a low point in the 1930s from which sown areas had hardly recovered (Squire et al., 2019). It was uncertain

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whether rhizobia that combined with legume crops to form the N-fixing symbiosis were still present.

The interventions in the integrated system are listed in the lower four boxes in Fig. 16 under the main components of the strategy:

- organic matter inputs;
- conservation tillage;
- nutrient supply; and
- pest management.

These interventions affect life forms to achieve improvements in soil biology, soil physics, crop health and invertebrate food webs, which combine to achieve goals for the environment, productivity and biodiversity. Progress is monitored by a suite of indicators:

- Soil microbiome and macro-invertebrates;
- Soil carbon and plant nutrient availability;
- Weed seedbank and emerged weed flora;
- Field-margin vegetation;
- Crop phenology and yield;
- Pollinator abundance;
- Predator activity-abundance patterns;
- GHG emissions; and
- Soil water quality.

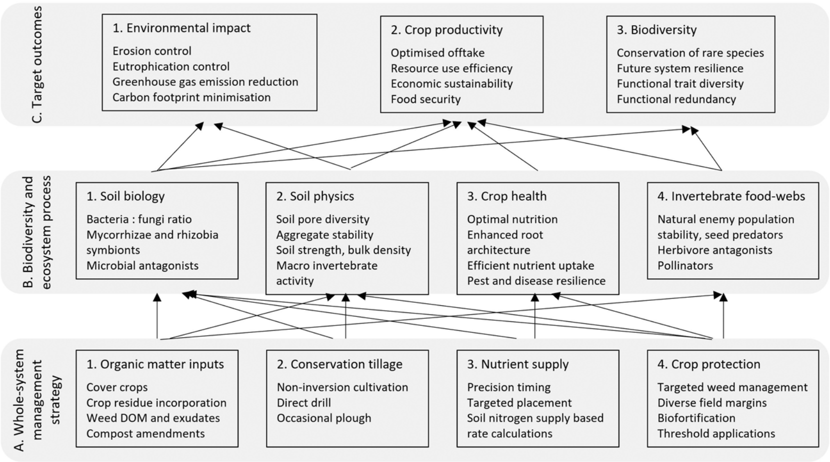

Figure 16 Integrated, outcomes-based approach to designing a regenerative cropping system for biodiversity, environment and food security: case study example from the James Hutton Institute's Centre for Sustainable Cropping long-term platform, Balruddery Farm, Dundee, UK (Hawes et al., 2019; Squire et al., 2022).

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The regenerative approach adopted at the CSC applies B for A to open up and regulate chains of effect to achieve high-level targets. Results to date include improved soil biophysical condition, reduced pesticide and fertiliser inputs and increased plant biodiversity. The presence of rhizobia and their capacity to fix atmospheric N in symbiosis with faba bean roots have both been confirmed (Maluk et al., 2022). The grain legume in the rotation coupled with integrated management converted a net N loss from cereals cultivation to a net N gain (Squire et al., 2022).

The portfolio approach was adaptable, in that interventions were modified based on findings. For example, after the first few years, no N fertiliser was applied before winter to reduce losses at times of very high rainfall, while an N-demanding crop was undersown with N-fixing clover to compensate for reduction of mineral N-input.

Activities in the right-hand panel of Fig. 12 are continuing through interactions between science, farming interests, communities and non-governmental organisations. The latter aim to improve all aspects of the food chain (Nourish Scotland, 2024) and promote on-line and in-person debates on the future of land, its management and its products (SEDA Land, 2024). The field research network and the CSC both reside within and contribute to agriculture and food production in an extensive bioregion that aims to achieve food security mainly from local producers (Bioregioning Tayside, 2024).

12 Conclusion

Transitions from degraded to restored agro-ecosystems are occurring in many parts of the world (SER, 2024). However, the more general trend globally and in most countries is continued degradation (FAO, 2019). Biodiversity is still in overall decline in both crops and in the microorganisms, flora and fauna that support agricultural production. Soil is losing structure and eroding in intensively tilled arable land and in upland shifting cultivation. Many ecological transitions fail to comply with the UN's guidelines.

In principle, the scientific knowledge of restoration is sufficient to underpin sustainable transitions in all but the most degraded land. Climate change is making such transitions more difficult to achieve (IPCC, 2023), but extractivism and conflict for land and resources are now a greater cause of mass hunger and famine than climatic extremes (GRFC, 2021). Political will in these circumstances, both within and across boundaries, is essential for progress (FAO, 2019, Chapter 9).

In those regions devoid of serious conflict, regeneration of agricultural land by B for A is entirely feasible. While the functional roles of many organisms contributing B for A are still unknown or uncertain (FAO, 2019) there is sufficient

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knowledge to guide regeneration. The main factors preventing the right transition are the dominance of global food chains, the reluctance of farming to move away from established practices, and limitations in policy, support and governance. If these obstacles are removed, regenerative practice at the scale of the patch, field and farm can undoubtedly restore the soil microbiome and the flora and fauna of farmland for greater system resilience and overall system sustainability.

13 Where to look for further information

Three sources are suggested for further reading: books, global reports, and organisations directly involved in regeneration.
Books:

- Evans (1993) *Crop evolution, adaptation and yield* is a standard reference.
- Pearson and Ison (1997) *Agronomy of grassland systems* covers grazing and livestock production in many parts of the world.
- Conway (1997) *The Doubly Green Revolution* 'Food for all in the 21st century' deals with ways to tackle the future demands for food and has several chapters relevant to IFM.
- Leakey (2012*) Living with the trees of life* describes the many uses of tree crops and makes the case for multifunctionality in agriculture.
- Findlayson and Warren (2010) *Changing natures* takes a critical look at transitions between hunter-gatherers and early agriculture.
- Tudge (2016) *Six steps back to the land* argues for a greater connection between people and land and a transition to more and smaller holdings.
- Azam Ali (2021) *The Ninth Revolution: 'Transforming food systems for good'* covers past failures (and successes) and presents the case for fundamental change.

Global reports tend to be highly detailed. The best place to begin in each case is the summary, which is sometimes released as a separate document available at the web links in References. Then by perusing the contents, the reader can usually find the topics of most interest.

- United Nations: *Principles for Ecosystem Restoration to guide UN Decade of Ecosystem Restoration 2021–2030* (FAO, IUCN, CEM and SER, 2021).
- The Society for Ecological Restoration: *International Principles and Standards for the practice of ecological restoration* (Gann et al., 2019)
- Food and Agriculture Organisation of the United Nations: *Status of the World's Soil Resources* (FAO, 2015); and *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019).

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Organisations that support and promote sustainable production and agro-ecological transitions:

- The Society for Ecological Restoration (SER): operates globally but points to many local restoration stories, some of which involve production land (SER, 2024).
- The Bioregioning movement: not explicitly about regeneration and farms but the movement is encouraging regions to think and act holistically to provide for their future including their agriculture and biodiversity. An example local to the authors is Bioregioning Tayside (2024).
- Organisations that practice and promote IFM: tend to be local to a country, for example in the UK there are Linking Environment and Farming (LEAF, 2024), Nature Friendly Farming Network (NFFN, 2024) and the Soil Association (2024).

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