Resilience in commercial forestry
Doing business with nature

A technical report by the University of Cambridge Institute for Sustainability Leadership

The University of Cambridge Institute for Sustainability Leadership

For 800 years, the University of Cambridge has fostered leadership, ideas and innovations that have benefited and transformed societies. The University now has a critical role to play to help the world respond to a singular challenge: how to provide for as many as nine billion people by 2050 within a finite envelope of land, water and natural resources, whilst adapting to a warmer, less predictable climate.

The University of Cambridge Institute for Sustainability Leadership (CISL) empowers business and policy leaders to tackle critical global challenges. By bringing together multidisciplinary researchers with influential business and policy practitioners across the globe, it fosters an exchange of ideas across traditional boundaries to generate new, solutions-oriented thinking.

Authors

The principal investigator and author of this report and the Summary report is Hannah Tranter of CISL.

Technical report

This technical report is part of a series of 'Doing business with nature' publications; these identify challenges and opportunities for companies whose future growth and sustained supply of nature's goods and its services, known as 'natural capital'. The rationale for investing in sustainable natural capital management is set out in Doing business with nature: Opportunities from natural capital and has been further developed through commodity-specific Action Research Collaboratories (ARCs) for Dairy in the UK and Ireland, for Cotton and for Commercial Forestry (described here).

Part 1. Commercial forestry and natural capital

Now, more than ever, companies are urged to recognise the fundamental role that nature's goods and services play in business operations.

Commercial forestry, which includes timber as well as pulp and paper, is fundamentally dependent on natural resources such as water, biodiversity, soil and carbon. To maintain competitiveness, differentiate themselves in the market and secure long-term resilience, companies along the supply chain should aim to manage the risks and opportunities associated with the natural environment.

A number of efforts and initiatives, including those spearheaded by the World Wide Fund for Nature (WWF), the Food and Agriculture Organization of the United Nations (FAO) and certification bodies, support companies in building sustainability and resilience. Within this context, companies are working to improve understanding of how practices on the ground and sourcing or purchasing decisions further up the supply chain can impact on natural resources.

As these resources are crucial for the long-term supply of raw materials and for resilient forestry systems, it is important to empower the forestry sector to better manage them. The sector has come a long way to improve the sustainable management of commercial forests. However there is now an opportunity to build on existing efforts by better measuring and communicating corporate impacts on natural resources. Such metrics would help inform internal decision-making, support supplier performance reviews and demonstrate progress to stakeholders, including customers and investors. The metrics, combined with science and technology, will enable industry leaders to address natural resource risks and build resilience in commercial forestry.

The report highlights how businesses in the forestry sector impact and depend on water, biodiversity, soil and carbon and looks at existing efforts to address the related challenges. It suggests that it is possible for the sustainable management of production landscapes to simultaneously benefit natural resources and build resilience in the commercial forestry sector. Better understanding of how commercial forestry impacts and depends on natural resources will facilitate the necessary research, collaboration and action going forward.

The ARC has produced two pieces of work:

- The Resilience in commercial forestry: Doing business with nature report presents the case for natural resources to be better considered in commercial forestry decision-making processes.
- This Technical report explores 11 different management practices and provides a preliminary assessment of evidence regarding the impact of these practices upon water, biodiversity, soil and carbon.

Part 2. How to use this document

The process of assessing the impact of management practices on natural resources is complex. Carrying out a preliminary assessment to suggest hotspot areas of risk can serve as a useful starting point.

Appropriate science, mapping tools and measurement indicators are essential for rigorous and context-specific assessment of impact. Nevertheless, it is possible to deduce indicative measures of impact on practices while keeping in mind important caveats. A preliminary assessment can highlight where decision-making efforts might need to be prioritised to mitigate natural resource risks.

There are a variety of management practices that are core to commercial forestry and others that are additional or optional. Eleven practices and their impact on natural capital were investigated:

Core commercial forestry practices
1. Selecting tree species
2. Thinning and pruning
3. Constructing roads, skid trails and landings
4. Harvesting

Additional and optional practices
5. Fertilising soils
6. Controlling pests
7. Tilling soils
8. Establishing drainage systems
9. Zoning natural habitats
10. Carrying out prescribed burning
11. Restoring lands

Practices and their impact are denoted as either positive or negative, but where insufficient or contradictory evidence was found, these are marked as limited evidence.

The 11 practices are evaluated against the following criteria:

Section	***Purpose***
Definition, relevance and caveats	• To briefly define the practice • To state the relevance of the practice to commercial forestry • To introduce caveats that need to be considered when assessing impacts
1 Impact on water	• Explores the impact of the practice on water quantity and/or quality
2 Impact on biodiversity	• Explores the impact of the practice on biodiversity abundance and/or diversity
3 Impact on soil	• Explores the impact of the practice on soil structure and/or fertility
4 Impact on carbon	• Explores the impact of the practice on carbon capture and/or storage

This report reviews some of the research that exists regarding the impact of commercial forestry practices on natural resources. A full list of the academic articles that were reviewed can be found in the References section. This list is not exhaustive, but was used to initiate a preliminary assessment.

Part 3. Translating research into expectations

To build rigorous impact assessments there are a number of indicators that can be mapped, measured and monitored. These indicators can help measure and review supplier performance and inform decision-making. Businesses can then translate expectations with regards to natural resource management into a clear set of guidelines and principles to provide direction to suppliers, internal colleagues and the entire supply chain. These can be underpinned by indicators as outlined in the Summary report. Table 1 provides an illustration of the types of questions that could be considered by suppliers in order to mitigate negative impacts and safeguard the natural resources that commercial forestry depends upon.

Core commercial forestry practices
1. Selecting tree species: What species were originally present and what species are being planted? Consider: ☐Species (exotic or native) ☐Stand origin (mature or second growth) ☐Stand composition (pure or mixed) ☐Seeds (genetically modified or conventional)
2. Thinning and pruning: What thinning methods are used? Consider: ☐ Intensity (thinning stand from below or heavy and pre-commercial thinning) ☐Residue biomass (leave or remove)
3. Constructing roads, skid trails and landings: What is the design, location and use of the roads, skid trails and landings constructed? Consider: ☐Design (culverts, unflooded vegetation bridges) ☐Location (in relation to species movement and migration, recorded vehicle road cling, forest regrowth along road margins ☐Use (use of de-icing salts, use and passage of heavy machinery)
4. Harvesting: What is the intensity, methods and location of cutting regimes? Consider: ☐Intensity (small-scale cutting, selective cutting, clear-cutting) ☐Methods (whole tree harvest, conventional, stem-only harvest and equipment used) ☐Location (controlled regrowth, slopes, relation to streams and channels)
Optional and additional practices
5. Fertilising soils: What types of fertilisers are being used, in what form and when? Consider: ☐Type (phosphate, potash, nitrogen, potassium, urea, lime, wood ash recycling) ☐Form (liquid or solid) ☐Season of application
6. Controlling pests: What methods are in place to prevent and control pests? Consider: ☐Preventative methods (herbicide and pesticide application, extending rotations) ☐Control methods (defoliation, transportation of attacked/diseased wood)
7. Tilling soils: What is the intensity of tillage practices and what is the existing soil profile? Consider: ☐Intensity (patch scarification, disc trenching, deep ploughing, industrial equipment used) ☐Existing soil profile (fertility, structure and composition)
8. Establishing drainage systems: What is the intensity of drainage systems and landscape observations? Consider: ☐Intensity (ditching severity, location) ☐Landscape changes (habitat structure, impact on peatlands, fens and swamps, flooding severity/frequency)
9. Zoning natural habitats: What are zoned areas comprised of and how are they laid out? Consider: ☐Comprised of (riparian areas, water catchment areas and wetlands, Intact Forest Landscapes - IFLs) ☐Layout (buffer strips, open spaces, edge habitats, wildlife bridges)
10. Carrying out prescribed burning: What are landscape impacts of burns and how do these compare to natural disturbances? Consider: ☐Landscape impacts (drought frequency, flooding frequency) ☐Natural disturbances (pests attracted to fire, wildfire activity)
11. Restoring lands: What is the original land use, the planted species and what are the methods used to restore the land? Consider: ☐Original land use (pasture, primary forest, abandoned/degraded, arable) ☐Planted species (native or exotic) ☐Methods (afforestation, reforestation, use of local knowledge, rehabilitation programmes)

Table 1: *Types of questions that could be considered by suppliers when carrying out core commercial forestry practices and optional or additional practices.*

Part 4. Core commercial forestry practices

1 Selecting tree species

Definition: selecting tree species in relation to site characteristics and local climate for sustainable management.

Relevance: Selecting appropriate tree species can be done to satisfy different economic, social and environmental objectives and will involve different trade-offs.

Caveats: Impact depends on species originally present and on what species are being planted

1.1 Impact on water: positive

- Tropical and subtropical species conversions to Eucalyptus hybrid plantations might exacerbate streamflow responses to extreme dry years even more than a pine plantation with a potential **streamflow reduction** of 20%[1,2].
- Can decrease the **apparent frequency of observed extreme wet-event years**. For example, converting native deciduous catchments to dense pine monocultures can reduce annual stream flow during both extreme wet and dry event years. This may exacerbate low flows and drought, but it may also potentially mitigate high flows and flood risk[2].
- Tree species and age impact on **transpiration**[3] and water quality is also affected indirectly through a difference in evapotranspiration.
- Tree species and age can also delay or accelerate **nitrogen leaching** as nitrogen retention and annual symbiotic nitrogen fixation differs with trees species[4].
- Greater leaf area can lead to a **higher interception rate of certain tree species** (greater interception losses in mature coniferous stands compared to broadleaved forests) which can modify spatial patterns of canopy through fall and stem flow[5].
- Deeper rooting from selected tree species, such as beech trees, and higher activity of soil macro-fauna can improve soil structure compared to other tree species, thus leading to **improved infiltration rates** and decreased surface runoff[6].

1.2 Impact on biodiversity: positive

- In intensely driven forests where yield in cubic meters has priority, exotic genetic varieties or species are prioritised. Moving away from native tree species will affect biodiversity and the **homogenous structure** of the plantation[7]
- Tree species can benefit biodiversity in certain plantations. For example, increasing the broadleaved area and number of native broadleaved species in conifer plantations is generally **beneficial to biodiversity**[8]
- Diversity of **fungal lichen and invertebrate communities has been shown to increase** in response to increasing broadleaved species. Intra-specific variation in different tree species may also be of importance for dependant biodiversity. For example, genetically modifying trees for resistance to pests and diseases can impact on the value of that tree species as host for a variety of organisms[9]
- Different tree species provide shelter for young trees, retain nutrients in forest environments prone to leaching, stabilise the upper soil horizon and **enhance mechanical impedance of soil**[10]

1.3 Impact on soil: limited evidence

- Impact on soil differs because different tree species vary in litter quality, activity of earthworms and soil microbial communities, root structure and rates of nutrient uptake and growth[11,12]
- Nutrient leaching will differ according to the species selected. Nutrients that are not taken up by the atmosphere **leach into the soil** but this depends on canopy architecture (height, leaf area index and aerodynamic roughness length)
- Soil pH and soil concentrations of dissolved organic carbon depend on **weathering rates** which vary according to different tree species[13,14]
- Tree species have significant impacts on the composition of **soil microbial communities**
- **Soil pH** is affected by individual tree species which shed different quantities of organic matter with different chemical composition[15]
- Soil quality can be preserved **by the correct selection of tree species** and species which lead to deterioration of the soil can be mixed in plantations with species that improve soil quality[11]

1.4 Impact on carbon: limited evidence

- Different species have **different capacities to build up carbon stock** in biomass and soil[10]
- Different species impact on soil carbon stock which **affects stand stability and resilience** against disturbances[16]
- Tree species selection effects **the decomposition of the forest floor** and can modify its quality (quantity and chemical quality of litter, rooting depth)
- Tree species selection sometimes looks at replacing old-growth forests with fast growing young trees or tree species that can sequester carbon faster but, at the same time, the **carbon storage is being reduced**[17,18]
- The impact of selected tree species on carbon depends on the direction of change. **Replacing broadleaves with conifers** increases soil, biomass and ecosystem carbon stock, net primary production and soil respiration, but a change in tree species the other way decreases carbon stocks[10]
- Sometimes no effect on soil carbon is found. The balance between the positive and negative impacts of the understorey vegetation on the carbon storage is therefore very much **dependent on the local site and management conditions**[10]
- The effect of tree species selection on carbon storage in stable soil pools is **controversial** and so far insufficiently proven[16]

2 Thinning and pruning

Definition: selectively removing parts of the tree, including branches, buds or roots.

Relevance: Thinning can be beneficial in terms of removing deadwood, maintaining health, preparing nursery specimens for transplantation and providing increasing light and rainfall to the forest floor.

Caveats: Impact depends on thinning methods used and on timing and intensity

2.1 Impact on water: positive

- In thinned areas, higher light levels correspond to increased exposure to evaporative forces. Thinning may therefore **increase evaporation** because more light, temperature and wind can cause a minor change in water balance.
- Thinning treatments can cause immediate **decreases in both leaf area index and rainfall** interception but this varies over time[19].
- Leaf area, resulting from pruning practices, influences evapotranspiration through interception and transpiration[2].
- Studies on coniferous tree species have shown that thinning of forest stands can result in **increased tree growth**, by apportioning the available soil water among few trees.
- Removal of intercepting surfaces of the forest canopy directly affects the generation of runoff and results in **higher water availability** - contributing to soil moisture and/or streamflow[3].
- The growth of thinned stands of several species has been related to **reduced soil water stress**, as a consequence of a reduction of both canopy interception and stand transpiration.
- **Predawn leaf water potential** is significantly higher in trees in thinned stands than in closed stands, as a consequence of higher relative extractable water in the soil.
- Heavy and early pre-commercial thinning leads to shorter rotation length and may **continuously reduce water consumption** compared to stands thinned from below[3].

2.2 Impact on biodiversity: limited evidence

- Different adopted methods have **different impacts** on biodiversity and comparing biodiversity in old-growth forests to managed forests can provide insight into the impact of thinning
- **Change the composition and structure** of the stand with increased complexity[20]
- Can **affect mycorrhizal fungi**, some negatively, some positively[7]. This depends on thinning and pruning intensity and methods used

2.3 Impact on soil: limited evidence

- Forest thinning changes soil temperature, soil water content, root density and activity and thus **changes in soil respiration** are likely as a result of the decrease in root density after thinning[21]
- Thinning can produce a load of residue biomass and depending on the methods and strategies used can impact on soil nutrition differently. If the residue biomass is removed, nutrient pools can be significantly decreased. If left on site, this can **increase topsoil ammonium** concentrations. This can then be followed by a moderate increase in soil solution nitrate with a peak concentration for a few months after thinning[22,23]

2.4 Impact on carbon: limited evidence

- **No evidence of long-term** effects of thinning and harvest on soil carbon
- Thinning **modifies the microclimate at the soil surface** generally improving temperature and soil moisture and decreasing temporarily the litter fall, thereby perhaps depleting the forest floor carbon pool[10,24]
- Thinning can increase stand stability at the **expense of the carbon pool size[16]**

3 Constructing roads, skid trails and landings

Definition: constructing roads to connect land, skid trails to move trees from landings to decks and landings to stack, store and load logs onto transport trucks.

Relevance: Integral to forest access systems for general management, maintenance, timber extraction and recreation. Roads and skid trails need to be appropriately located to minimise soil erosion, reduce compaction, improve efficiency and decrease site impacts.

Caveats: Impacts depend on number, design, location and use and on the design and layout of culverts

3.1 Impact on water: negative

- Depending on design, location and the surface area impacted, road construction and associated engineering related to road surfacing, drainage and culvert design can permanently **alter hydrologic flow paths** of forested watersheds[2]
- Road construction can increase peak runoff and promote **changes in peak discharges** in basins, modify water flow paths and speed up the delivery of water to channels during storm events[25]
- Unless frequent culverts are installed, filled areas impede drainage, especially in tropical regions that receive heavy wet-season rainfall. This can lead to **extensive flooding** on the upstream side of the road, killing large patches of inundated vegetation and can cause stream sedimentation[26]
- In certain forests, the use of de-icing salts, as linked to road construction, can **alter soil and aquatic chemistry** and harm roadside vegetation[26]
- **Carefully planning and constructing** roads, decks, stream crossings and skid trails can help minimise bare soil, rapidly revegetate areas and support streamside management zones[27]
- Destructive flooding can be minimised and stream flows maintained by the **establishment of large culverts** under roads. These should be designed so that increased stream velocity within them does not create a barrier to aquatic fauna[26]

3.2 Impact on biodiversity: negative

- For species with limited dispersal abilities, roads, tracks and other infrastructures may act as barriers and **eliminate or limit migration**
- Roads may **reduce landscape permeability** for certain species, including ground beetles and butterflies[7]
- Roads can create artificial firebreaks, leading to a **proliferation of mesic vegetation** at the expense of fire adapted species[26]
- Some species suffer heavy mortality near roads from **vehicle road kill**, elevated predation or human hunting. Although narrow forest roads facilitate road-crossing movements by animals, they also lead to greater road kill[26]
- Barrier effects on wildlife can be minimised by **limiting road widths** and maintaining a nearly continuous canopy overhead, although such measures can increase road kill because road crossing movements are more frequent
- **Regrowth forest** along road margins can reduce isolating effect of roads
- Bridges over watercourses that include a **corridor of unflooded vegetation** and natural streambeds are especially effective for maintaining connectivity, both for terrestrial and aquatic fauna and can mitigate against the negative effects of road construction[26]

3.3 Impact on soil: negative

- Road construction may lead to restricted root growth, soil compaction, increased bulk density and loss of soil porosity. This will **deteriorate the root environment** and will lead to lower production rates
- The first few passages of heavy and large machinery **removes organic matter** from the forest floor and changes soil nutrient availability[28] which might influence weathering rates and nitrogen mineralisation[29,30]
- If constructed near surface water, roads can **speed up erosion** and cause compaction which result in changes to pore size distribution, soil moisture content, root environment, root and tree growth, mortality and promotes sedimentation in lakes and streams[11]
- **Compacted soils** restrict air supply to tree roots, decrease capacity of the soil to store and retain water and reduce root penetration, extension and germination[11]
- Constructing roads can cause a **substantial loss of habitat** for most soil fauna
- **Focussing on a few selected trails** can minimise trafficking in other areas and limit the area of compacted soil
- Soil erosion and stream sedimentation can be reduced by **confining the use of heavy equipment to drier months** and by **seeding fast growing native plants** over road cuts and disused quarry sites[26]

3.4 Impact on carbon: limited evidence

- Building and maintaining roads uses energy and releases carbon dioxide and greenhouse gases to the atmosphere, thereby countering the effects of carbon storage and sequestration by the forest itself
- An efficient road network can reduce the carbon dioxide and greenhouse gas emissions from vehicles used to transport machinery and extract timber

4 Harvesting

Definition: involves clear-cutting or removing products from a forest to make room for a new generation of trees.

Relevance: While harvesting modifies wildlife and alters natural systems, it is fundamental to commercial systems.

Caveats: Impacts depend on scale, configuration, timing and location of cutting and on area's natural disturbances and timing compared to harvesting regimes

4.1 Impact on water: negative

- Harvesting promotes a change in evapotranspiration which **drives a change in runoff**
- Harvesting can **increase moderate peak flows** immediately downstream[31]
- Forest harvesting reduces transpiration and increases water yield from the site during the growing season. The increased soil disturbance and water movement caused by timber harvesting results in slight, but measurable **increases in stream sediment** and nutrients[27]
- Harvesting reduces interception losses and eliminates transpiration to cause **an increase in water yield** for the first few years until the clear cut area becomes re-vegetated[32]

- Harvesting can cause a **dramatic increase in leaching of nutrients** from a catchment scale clear-cut. Peak concentrations in nitrate appear 2-3 years after clear-cut in soil and stream waters. The nitrate concentration often returns to pre-cutting levels within a relatively short time 3-5 years
- Forests can be eroded through intense logging which can impact **aquatic food chains**[33]
- Harvesting causes **erosion** to increase and so increases sedimentation in water bodies and surface waters[34]. Erosion is especially bad if harvesting is performed on steep slopes[35,36].
- Reduction of forest cover generally increases water yield but response to harvesting is **highly variable**[37]
- Assumed 40 mm **increase in annual yield** for every 10% reduction in conifer forest or eucalyptus forest cover and 25 cm increase for deciduous forests[38]
- Greater infiltration rates and water yields can be obtained depending on **configuration and timing of cutting**, location of cutting in relation to the stream channel or source area, and whether regrowth is controlled

4.2 Impact on biodiversity: limited evidence

- Harvesting can create fragmented forests which impacts on species such as Saprozylic beetles, especially species living in hollow trees that require **continuity of substrates**[39]
- Harvesting can cause **bird species adapted to permanent tree cover** to decrease (often non-migratory birds). Amphibians are also often negatively affected by harvesting[40]
- Impact on biodiversity can be positive or negative depending on which species or species group are considered and **how the cutting has been carried out** in relation to the natural disturbances in the area
- **Small-scale cutting** (e.g. small groups <0.25 ha or individual tress) is an alternative harvesting method to clear-cutting and can reduce impact
- **Selective cutting**, including thinning and small felling, can promote regeneration and affect the abundance and quality of dead wood in the new stand
- Species adapted to large-scale disturbances might benefit from clear-cutting provided that **suitable habitats and substrates are created**
- Some clear-felling may be appropriate to **conserve biodiversity**[41]. Vascular plants are an example of a species group which is less affected by clear-cutting, or which might even benefit from clear cut harvests[42,43]
- Species richness can be 30-35% higher 5-8 years after logging compared to the old forest and the number of species can almost double in clear cuts compared to mature herb-rich forests[44]. When the abundance of **herb species increases, this benefits several mammals** (rodents and cervids) and **some predators** such as red fox, wolves and lynx benefit from increasing abundance of rodents and cervids[45]
- Many other species common in the agricultural landscape, **associate with open or semi-open grassland and bushes** are favoured by clear cutting[43]

4.3 Impact on soil: negative

- Short rotation forestry and harvesting can **decrease arthropod diversity,** especially collembolans and mites, which are important for keeping the soil fertile by making adventitious port structure[7,46]
- Harvesting causes significant decrease in the soil content of almost all nutrients and an **increase in soil acidification,** depending on the weathering capacity of the soil minerals and intensity of biomass removal[14,47,48]

- Harvesting impacts the **nutrient stock and availability**, soil acidity, content of carbon, soil nutrient, turnover of organic matter, mineralisation rates and soil biology
- Magnitude of **soil loss** depends on post harvesting canopy cover, plant density, depth of the forest floor and presence of woody debris[49].
- Forest harvesting equipment has evolved considerably during the past decade from man-held chain saws towards mechanised heavy machinery which might cause **increased compaction**, increased bulk density, loss of soil porosity and increased erosion. Soil disturbance from harvesting machinery is influenced by factors such as the amount of litter and slash on the forest floor, soil texture, soil moisture, weight of harvest machines along with the weight of the logs, wheel size and pressure, speed, operator skill, operation planning, the use of technical equipment such as mobile bridges, terrain and weather[29].
- If performed intensively harvesting may be an important source of **acidity** and increase the loss of base cations[50-53].
- Canopy removal by thinning and clear-cut harvesting temporarily increases the amount of precipitation and sunlight reaching the forest floor, reduces transpiration rates and causes soil moisture to increase, leading to more **favourable conditions for decay microorganisms** (decomposition and mineralisation)[54,55].
- Canopy removal maintains soil temperature and the net effect is **sustained nitrification and nitrogen mineralisation** when plant uptake is disrupted and nitrogen demands are low[11]

4.4 Impact on carbon: limited evidence

- Trees absorb CO_2 from the atmosphere and store it in biomass. Harvesting could reduce losses from decomposition of biomass in mature forests.
- Effect on soil carbon is small and depends most on the **management of residue** (left on site, burning ,none etc) and if they are counted as a loss or as a carbon input to the soil[10,16,56]
- After harvest or thinning the **rate of decomposition of slash** on the ground is higher than accumulation of carbon in the vegetation and soil[57]
- Whole tree harvest (compared to conventional or stem-only harvest) removes up to 2-4 times more nitrogen from the forest due to lower **carbon:nitrogen ratios in foliage and branches**[22]
- **Long rotation period** ensures less disturbance from harvesting practices to carbon stocks[16]

Core commercial forestry practices

5 Fertilising soils

Definition: increasing soil fertility to improve forest productivity and inputs through applications to the soil, including liming and recycling wood ash.

Relevance: Inputs can maintain soil fertility by improving chemical and biological soil properties, can shorten rotation lengths with trees reaching merchantable size at a younger age and can improve yields substantially.

Caveats: Impact depends on type of fertiliser used and on timing and existing soil conditions

5.1 Impact on water: negative

- The use of fertilisers (e.g. phosphate, potash, nitrogen and potassium) is common to encourage tree growth in nutrient poor upland soils. Nitrate concentrations in the soil can also increase as a result of bacterial breakdown of brash. Approximately 10% of an aerial application of phosphate fertiliser can be **lost in run-off** during the first three years after application, impacting on water quality, but losses thereafter are small[58]
- **Nitrate concentrations** in seepage water peak after fertilisation and is higher than the concentration in streams due to denitrification and other nitrate processes in the riparian zone, in stream removal and in mixing with other water[22]
- Fertilisation may have indirect effects on **water uptake** by changing the shoot to root ratio, rooting pattern and conductivity properties of the xylem
- Fertilisation may influence evaporation and transpiration by altering leaf area and by changing stomatal behaviour. This may therefore lead to **higher interception losses**[3]

5.2 Impact on biodiversity: negative

- Urea fertilisation **declines understory vegetation** dramatically, with a drop of up to 10 fold in herb layer cover in unthinned stands of temperate forests
- Fertilisation can **decrease species richness** across a range of spatial scales
- Fertilisation can impact on **tree canopy cover and density** and can decrease understory light levels. It can therefore have large effects on understory plant diversity and community composition[59]
- Fertilisation can have long-term affects on **soil fauna** (predatory macroarthropods). This depends on season and fertiliser form (solid or liquid). Solid fertiliser in autumn causes decreases in soil fauna while liquid fertiliser causes increases.
- There can be clear **shifts in community composition** following both liquid and solid forms of fertilisation, but species number and diversity are not significantly affected. This is likely due to increases in tolerant species that balance decreases in other species
- Fertilisation effects on species composition of the forest floor vegetation within one forest rotation have been extensively documented. Important vegetation changes start to take place when adding low nitrogen doses in boreal forests, but recovery of the vegetation after ceasing nitrogen input is a very slow process. **Changes in key ecosystem components** occur even at a lower rate of nitrogen input than the present understorey vegetation so there is a need to look at minimising critical loads[60]

- **Liquid fertilisation** has fewer negative impacts on many species than fertilisation in solid form[61]

5.3 Impact on soil: positive

- Fertilisation can increase nitrate in the soil solution, **decrease forest floor carbon to nitrate ratio**[62] and increase forest floor pH which stimulates net nitrification[22,63]
- Liming and wood ash recycling are suggested as a tool to **counteract the acidification** of forest soils and the loss of base cations[64]
- More research is needed on the long term effects of soil fertilisation, as well as on how fertiliser nitrogen is immobilized following fertilisation and how it is then released following harvest or tillage
- Fertilisation impacts on **biological and chemical processes** which influence nitrate mobility and plant requirements for nitrogen
- Application of wood ash is suggested as an alternative to lime and as a means of **recycling nutrients** removed from the forest ecosystem in logs[22]
- Fertiliser additions cause a **significant decrease in foliar concentrations** of all nutrients except for nitrogen[11]
- Liming and wood ash recycling **raise pH of upper soil** (especially untreated ash) - this may have long term effects. However the transport of ash components down through the profile can be slow and so an increase in pH is not always obvious
- A few studies suggest that liming should **be followed by another type of fertilisation** to avoid negative impacts on growth[11]

5.4 Impact on carbon: limited evidence

- Liming and wood ash recycling increases soil pH and the **mineralisation rate of carbon** from forest floor[10,65]
- Liming and wood ash recycling cause **net loss of carbon** from forest soils in temperate and boreal forests owing to increased microbial activity and dissolved carbon leaching[10,66]
- Liming and wood ash recycling can decrease carbon stock and can lead to **emission of potent greenhouse gases** from soils[16]
- The effect on soil carbon depends on interaction of **litter production** by trees and carbon use efficiency of soil microbes[16]
- Fertilisation can **decrease mineralisation rates of the organic matter**[67] and increases the carbon flux into litter fall resulting in a net increase of the amount of carbon stored in humus layers and mineral soil[10]

6 Controlling pests

Definition: controlling pests through pesticide application, prevention of pest introduction, integrated pest management or changes in stand composition.

Relevance: Controlling pests promotes resilient forests and protection against native, alien or invasive insects to safeguard productivity.

Caveats: Impact depends on methods used to prevent pests and on practices used to control pests

6.1 Impact on water: limited evidence

- Apart from clear cutting the single most divisive issue in forestry related to water quality has been the use of **silvicultural chemicals**. The forest floor is essential to absorbing pesticides and preventing leaching and surface runoff and its condition will effect chemical leaching rates and water quality[68]

6.2 Impact on biodiversity: limited evidence

- **Impact of the use of pesticides is generally limited** in comparison to other growing systems (agriculture and horticulture) but does apply to short rotation forestry[7]
- **Preventing pest introduction and incidences** can safeguard local biodiversity
- There are generally **limited effects of pesticides on non-target organisms**. The closer production and management methods resemble intensive agriculture the more negative consequences on biodiversity are expected[7]
- **Extending rotations** in temperate plantations can diminish the influence of pests and disease and can benefit species associated with late succession forests such as lichens. Although there is evidence that species can adapt to plantation forestry and ecologically short rotations[7]
- **Roads** are often used to control pests by transporting attacked and diseased wood out of the forest. Roads can reduce landscape permeability and affect species migration

6.3 Impact on soil: limited evidence

- Herbicide application can reduce organic carbon, total nitrogen mass and acid phosphatase activity[69]. All weed removal methods **disturb the soil** to some extent[11,22,70-72]

6.4 Impact on carbon: limited evidence

- One pest control method, **defoliation**, or removing leaves from trees, can result in insect faeces, dead caterpillars, unconsumed green foliage thereby causing a pulse of nitrogen and labile carbon to the forest floor [73]

7 Tilling soil

Definition: fracturing the soil profile after soil has been compacted and soil structure has been lost to foster appropriate soil structure.

Relevance: Tilling the soil can increase soil porosity, improve aeration, allow root systems of perennial plants to occupy the soil and is therefore sometimes carried out to build more sustainable forest systems.

Caveats: Impact depends on depth of tillage practice and on existing soil profile and texture

7.1 Impact on water: limited evidence

- Tilling forest soils by most industrial equipment can increase soil density and destroys soil structure which can **reduce the ability of the soil to store water for tree**s.

- On the other hand, tilling can add several centimetres to soil depth and so **increase water retention** and holding capacity which are likely to be sustainable if no further trafficking occurs
- Tillage can have greatest impact on perennial forest species because changing soil aeration and **water supply** can significantly affect their ability to maintain their perennial root systems[74]
- Tillage of forest land changes infiltration and runoff characteristics, which affect **groundwater recharge, sediment and water yield, and evapotranspiration**
- Patch scarification, disc trenching and ploughing can improve growth and survival of seedlings but may lead to **leaching of nutrients**[11,75]

7.2 Impact on biodiversity: limited evidence

- Tillage, or scarification is negative for some vascular plants as **disturbs species composition**, species richness and abundance[7,76]
- Can affect **vegetation cover** for a long time after treatment
- Scarification is positive for some vascular plants **adapted to disturbances**[44,45]
- Deep ploughing and tilling is preferred preparation for afforestation because it **reassesses weeds more efficiently** than the other mechanical removal methods carried out before stand regeneration[11,75]

7.3 Impact on soil: limited evidence

- Tillage is frequently employed to decompact soils and **improve soil productivity**, but long-term consequences of soil nutrient depletion may be of concern[77]
- Effective soil tillage loosens soil and **increases the elevation** of the soil surface; unstable soil will consolidate over time
- Tilling can result in **removed forest humus** and decreased nutrient availability in the mineral soil
- Tilling can cause considerable disturbance to the soil profile since horizons are mixed and turned up and down in this way **disrupting the pedogenic processes** by which soil is formed[11,78]

7.4 Impact on carbon: limited evidence

- Most soil preparation techniques **speed up the mineralisation** of carbon and nutrients from soil organic matter and forest floor. Soil carbon generally increases with intensity of technique[79]
- Tillage affects positively the **photosynthetic carbon uptake by trees**, the gross primary production[10]
- Subsoil layers in the tilled areas can **intercept more organic carbon**[80]

8 Establishing drainage systems

Definition: adjusting the water content of the soil to a level to control runoff from sites as part of ground preparation work prior to commercial tree planting.

Relevance: Drainage systems create a favourable planting site for new transplants by loosening compacted soil, removing surface water and creating a raised planting position to lessen the effect of competing vegetation.

Caveats: Impact depends on timing of draining and on location and alignment of ditches

8.1 Impact on water: negative

- Changes in water transport characteristics and in the pool of 'plant available' soil water will probably be beneficial to tree growth in the drained area[81], but may **alter catchment hydrology**, increase sediment erosion and transportation and alter stream water chemistry
- May result in direct transport of **leached nitrate to streams** (where denitrification may otherwise have been a significant sink for nitrate retained in the wetlands) and export ammonium and organic nitrogen to forest streams[22]
- Extensive draining and logging may drastically **alter the structure and function of streams** even though the streams themselves are left untouched[82]
- Increase in mineralisation rates may cause a surplus of available nutrients with **significant leaching** to ground water or water streams as a consequence
- Impacts are very dependent on site conditions and peat thickness and can increase the loss/output of soluble organic carbon to watercourses in soils with the high **accumulation of surface humus** in waterlogged peat areas
- Poor forestry drainage can result in localised downstream flooding
- Drainage ditches are often **aligned at right angles** to the slope, with interception ditches to reduce run-off within the plough furrows

8.2 Impact on biodiversity: limited evidence

- Forest drainage causes clear **changes in habitat structure** as well as in the species richness and composition of moss-dwelling invertebrates in headwater streams [83]
- Quite a **permanently damaging activity of wet habitats** such as peatlands, fens and swamps. For example, in northern Scotland, planting on deep peat leads to erosion and loss of habitat for wading birds[7,84]

8.3 Impact on soil: negative

- Drainage of wetlands and subsequent oxidation of organic compounds can **mobilise large amounts of stored organic nitrogen**[22]
- In drained areas, flux measurements operated on forest stand, evidenced much **higher rates of soil respiration**
- In the long term, severe ditching may **reduce the nutrient capital** especially on bogs, relying on nutrients from precipitation
- Drainage exports phosphorus and ammonium nitrogen from watersheds

8.4 Impact on carbon: negative

- Drainage of peatland enables the establishment of forests (increased carbon storage in the biomass) and decreases methane emissions from soil, but is linked to the **increased release of carbon dioxide and nitrous oxides from the soil**[16,10]
- Drainage can decrease peat thickness which affects **peat carbon densities and peat carbon stores**
- Most peatlands emit methane and it is not known whether the drainage and afforestation of peatland may lead to a **positive or negative effect** on the greenhouse gas balance and carbon stocks[85]

9 Zoning natural habitats

Definition: actively managing zones as natural habitats to prioritise biodiversity conservation.

Relevance: Natural habitats, in the form of protected reserves, high conservation value areas, intact landscapes or ecological networks, which include corridors and buffer zones are crucial to maintaining the functioning of ecosystems and facilitating the conservation of species and habitats.

Caveats: Impact depends on size and location of zoned area and on native diversity and ecosystems

9.1 Impact on water: positive

- Zoned natural habitats and high conservation value areas can include riparian zones to **protect streams and water flow**
- Zoning and protecting specified habitats can secure the **watershed protection function** of forests
- Zoned natural habitats can include water catchment areas to ensure **protection of water quality and quantity**
- Natural forest habitats regulate **local water supply and quality**

9.2 Impact on biodiversity: positive

- Management in zoned natural habitats may be necessary as vegetation succession, if left unchecked, may lead to **loss of valuable species**
- Wildlife fences are made to keep out deer from new plantations; **exclusion of grazing animals** from areas of woodland can have both positive and negative effects on biodiversity and the impact of grazing as a natural disturbance varies a lot between different forest ecosystems
- Zoning using fences may be counterproductive; deer fencing is used to encourage and protect tree regeneration but can lead to a **decline in ground flora diversity**, resulting in the development of a large dense sward and the build up a vegetation mat, which ultimately can inhibit the regeneration the fencing was designed to promote
- In boreal forests the moose is a key species and its **browsing creates opportunities** for a number of species. So it should not be restricted to certain zones[86,87]
- Theoretical considerations from species models formalise the almost ubiquitous observation that **large contiguous forest areas** contain more biodiversity (especially species) than small and isolated stands and therefore zoning of natural and non-natural habitats should be avoided[88]
- Native and natural habitats that are zoned off for protection are by far the most important factor in determining the **biodiversity value** of a commercial landscape[89]
- Suitable management of protected areas may secure ecosystem, species and genetic diversity and therefore **improve stand resilience** to epidemics[7]
- Retaining structure by zoning natural habitats can **maintain associated ecological functions** and processes, preserve genetic information of trees, shrubs and associated biota, maintain structural complexity, improve connectivity between cutting units and forested areas and serve as a ‘lifeboat’ habitat for organisms that might otherwise be lost temporarily or permanently[90]

- Wildlife bridges can be a type of natural habitat that are constructed to facilitate highway crossing of deer, toads/frogs and dormouse and **allows species movement** inside and outside the forest
- Natural habitats including open space and edge habitats are often **key features for biodiversity** in managed forests and can include areas of unimproved scrub, treeline/montane scrub, grasslands, bogs, heaths and limestone pavements. Many birds depend on the maintenance of a **diverse edge structure**[91] and butterflies require nectar sources and food plant associated with edges and open areas[92]
- Natural habitats that are zoned off for protection include wet areas, lakes, ponds, streams, fens, bogs and marshes that provide **valuable aquatic habitats**[93]
- Natural zones including riparian areas can have high biodiversity value as they contain a diversity of habitats and **act as important corridors** for the movement of wildlife[94]
- **Maintenance of bank processes** and natural habitats supports a wide variety of wildlife but heavy shading trees can mean that some river banks are relatively species poor
- Sometimes it is only possible to **conserve species and their habitats** through strict protection and zoning of natural habitats
- Dispersal capabilities of threatened species can be enhanced by management to increase **landscape heterogeneity** and improve the 'permeability' of the matrix between natural habitat patches. For example, by leaving legacies on clear-fells or doing variable density thinning

9.3 Impact on soil: limited evidence

- Protecting natural habitats can help **control erosion** on vulnerable soils and slopes
- Natural habitats can retain soil **nutrient budgets and structure**

9.4 Impact on carbon: limited evidence

- Natural habitats such as Intact Forest Landscapes (IFLs) **store vast amounts of carbon** and also uptake of carbon from the atmosphere

10 Carrying out prescribed burning

Definition: burning a predetermined area to decrease the risk of intense fires by reducing the fuel build up in the forest floor.

Relevance: Prescribed burning stimulates the germination of some desirable forest trees, may improve wildlife habitat, control competing vegetation and tackle disease.

Caveats: Impact depends on frequency and geologic, topographic and intensity of burns and on the amount and intensity of precipitation, soil and cover characteristics

10.1 Impact on water: negative

- Burned lakes contain **higher concentrations** of total phosphorus (threefold), higher levels of total organic nitration (two fold) and potassium, chlorine and calcium can be higher by up to six fold. The concentrations of nitrate and sulphate can be up to 6 times higher in burnt lakes. Mobile ions released by fire (potassium chlorine and sulphate and nitrate) are rapidly flushed out of the watershed, but others show little change[95]
- In Mediterranean forest areas, **fires increase runoff and sediment yield** rates relative to undisturbed forested land especially in first rainfall seasons[96]

- Prescribed burning can result in increases in stream and peak flows which could lead to **channel instability and degradation**
- Fire promotes drought, and therefore more fire, by releasing smoke into the atmosphere, thus **reducing rainfall** in the forests of the Amazon[97]
- Prescribed burning leaves the land vulnerable to flooding and off-site downstream degradation of streams, lakes and reservoirs [98]
- Prescribed burning impacts physical characteristics of water including sediment yield, **turbidity** and increased water temperature[98]
- Following forest fires, water may be subject to increased production of macronutrients, micronutrients, basic and acidic ions, decreased oxygen level and increased **biological demand**[98]

10.2 Impact on biodiversity: limited evidence

- Mycorrhiza fungus has been shown to respond to fire by fructification[99]; some species regarded as **pests are also attracted to fire**, e.g. the longhorn beet *Monochamus sutor* and the wood wasp *Urocerus gigas* may cause economical damage on the wood[100].
- Some species adapted to post-fire biotopes are **able to survive** on clear cuts[101]
- Several bird species are favoured by the **variation in the landscapes** created by fires
- In unmanaged forests, fire generates **new stages of succession** and contributes to a variation in age and species composition within and between areas[102]
- In forests which are not adapted to fire, prescribed burning can kill virtually all seedlings, sprouts, lianas and young trees because they are not protected by thick bark. **Damage to the seed bank, seedlings and saplings** hinders recovery of the original species [103]
- Soil heating directly **affects microorganisms** by either killing them directly or altering their reproductive capabilities

10.3 Impact on soil: limited evidence

- Combustion of litter and soil organic matter increases the **availability** of some nutrients, although others are **volatilized** (for example nitrogen, phosphorus and sulphur)
- Burning may cause **a loss in soil** organic matter which affects cation exchange capacity, organic chelation, aggregate stability, macro pore space, infiltration, and soil microorganisms
- **Nitrogen replenishment** must be emphasized when prescribed burning programs are planned
- Soil properties located on, or near, the soil surface are more likely to be changed by fire because they are directly **exposed to surface heating**
- Prescribed burning can result in **high concentrations of available plant nutrients on the soil surface** immediately following fire
- **Bulk density** increases as a result of the collapse of the organic-mineral aggregates[104,105] and the clogging of soil pores by ash or feed clay minerals causing a decrease in the water holding capacity of soil[106,107]
- Prescribed burning leaves the land exposed to effects of wind and solar radiation resulting in **soil hydrophobicity** and soil erosion
- **Increase in pH of soil** after a fire due to hydrolysis
- Prescribed burning can cause substantial losses of nitrogen, carbon and sulphur through **volatilisation** or leaching even at low temperature. More prolonged burns tend to result in greater losses[11]
- Smoke from fires can significantly **reduce photosynthesis** and can be detrimental to species health[103]

- Prescribed burning can **build up the fuel load** in the soil by opening up the forest floor to drying by sunlight[103]

10.4 Impact on carbon: limited evidence

- The impact of prescribed burning **depends on intensity** but may mineralise most of the biomass stock, a variable part of the ground floor and soil stocks and lower the photosynthetic carbon uptake to zero. Light fires do mainly **transfer some carbon from the biomass to the soil** without subsequent depletion in productivity[10,108]
- Peat fires **release significant amounts of carbon dioxide** and other greenhouse gases
- Instead of acting as carbon sinks, Earth's northern boreal forests could start **releasing carbon at a faster rate than they can capture** it through wildfires and prescribed burning
- Prescribed burning is a potential way to **manage carbon dioxide fluxes** from forests in regions with high wildfire activity such as the western United States. Managing forest fuels with prescribed fire requires repeated application at a frequency that is appropriate to meet management goals. Low intensity fires **limit the risk of catastrophic events**[16]

11 Restoring lands

<u>Definition:</u> re-instating ecological processes to accelerate the recovery of forest structure, ecological functioning and biodiversity levels for stable forests, recovered biodiversity and environmental protection.

<u>Relevance:</u> Restoration enables the land to regain ecological integrity and ensure resilient systems. Economic benefits result from increased productivity from previously degraded lands and can offer new livelihood opportunities for forest-dependent communities.

<u>Caveats:</u> Impact depends on original land uses and on methods used to restore land

11.1 Impact on water: limited evidence

- Protection of riparian areas and buffer strips can facilitate denitrification and nitrogen retention and **protect aquatic systems**[22,109]
- Forest restoration can **increase in the mean annual streamflow** for individual watersheds by restoring ecological functions

11.2 Impact on biodiversity: positive

- **Increases the biotic homogenisation and decreases genetic diversity** of planted species may be a risk for biodiversity, especially as an increasingly popular form of forest restoration in tropical regions is widespread plantations of a small number of native species
- Monoculture tree plantations on restored land may facilitate establishment of invasive species and **increase susceptibility to species specific pathogens**[110]
- Restored forests and plantations can **improve ecosystem services** and enhance biodiversity conservation, but will **not match the composition and structure of the original forest cover**[111]
- Planted forests established for restoration purposes (ie to regain original forest structure, ecological functions and species composition, or to enhance landscape connectivity) usually involve the use of larger numbers of native tree species and reliance on **forest successional processes** [112,113]

- Restoration can **reinstate many ecosystem functions** and recover many components of the original biodiversity, when approaches take into account the spatial distribution, abundance and quality of residual vegetation
- Enrichment planting using native species in degraded forests can help to **stimulate natural succession**[88]
- Managed forest (e.g. traditional agroforests and forest plantations) can be structurally and/or floristically complex, **supporting higher native species diversity** than non-forest uses such as pasture and annual crops[114]
- Habitat restoration **needs more research** on how ecosystems will develop overtime, especially given climate change[7]

11.3 Impact on soil: positive

- Areas with degraded soils, rehabilitation through planting of carefully selected exotic or native trees **can improve soil fertility,** enhance nutrient budges and soil structure and restore productive land use
- Considering local knowledge of tree characteristics, planting of diverse species of ecological and economic importance and **integration of rehabilitation programmes** with regional development strategies are essential elements of restoration success[115]

11.4 Impact on carbon: positive

- Conversion of arable land to forest (arable land and pasture converted to forest) removes additional carbon dioxide from the atmosphere and **stores it in tree biomass**; thereby increasing the carbon stock on that land[10]
- Land-use changes such as those which result from afforestation and management of fast-growing tree species have an immediate effect on the **regional rate of carbon sequestration** by incorporating carbon dioxide in plant biomass
- Afforestation of former agricultural land increases the carbon pool in the **aboveground biomass and replenishes the soil carbon pool**[16]
- The management of existing forests can also increase carbon sequestration but earlier reviews found **conflicting evidence** regarding the effects of forest management on soil carbon pools[16]

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