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ECOLOGICAL EFFECTS OF LOGGING AND APPROACHES TO MITIGATING IMPACTS

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History and significance of logging

Globally, approximately 31 per cent (1.2 billion hectares) of forests are primarily managed for wood production, with a further 25 per cent designated for multiple uses including wood (FAO 2010). Wood removals are valued at around $100 billion annually and forest management thus represents an important source of employment (Figure 30.1; FAO 2010). Historically, logging was motivated by demand for firewood, housing materials and agricultural land, although the extent of logging and current trends differ substantially amongst biomes.

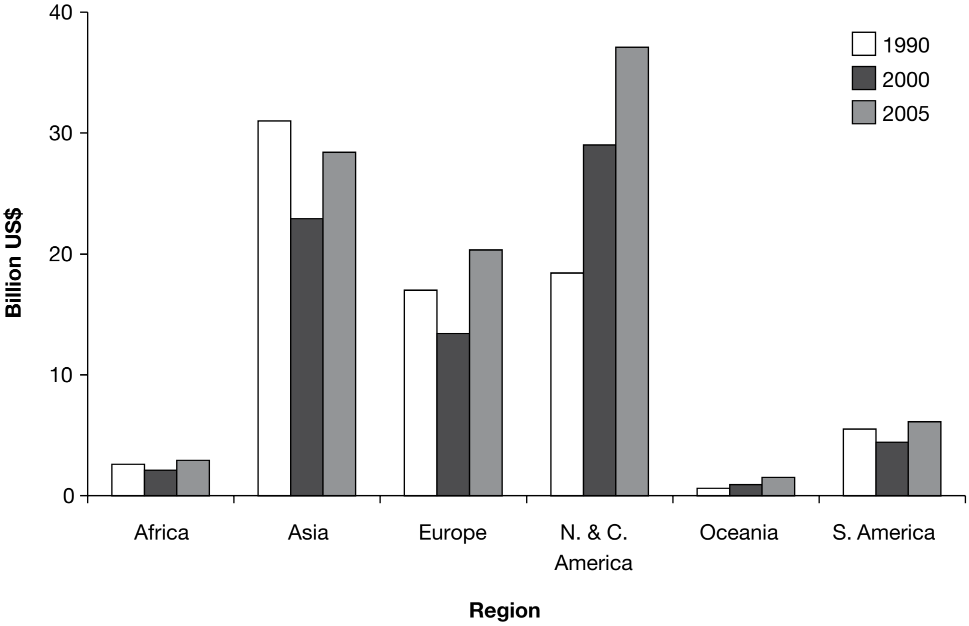

Figure 30.1 Value of wood removals (billion US$) by region in 1990, 2000, and 2005

Source: FAO (2010), *Global Forest Resources Assessment. Main Report*. http://www.fao.org/docrep/013/i1757e/i1757e00.htm (adapted with permission).

In Europe, logging of temperate forest dates back at least 5,000 years and from the fifteenth century became increasingly important for providing timber for shipbuilding, with demand for tar and charcoal also driving logging in boreal regions (Wallenius *et al.* 2010). Two centuries later, logging in North America followed a similar pattern. Consequently, although remote regions of Europe and North America retain significant areas of natural forest, logging in boreal and temperate biomes now occurs primarily in semi-natural and plantation forest (Brunet *et al.* 2010; FAO 2010). In contrast, until the 1950s, logging in the tropics was geographically restricted and either motivated by demand for fuel and housing, or focused on selectively harvesting precious woods such as mahogany and ebony. Improved transportation and increased availability of machinery has resulted in a rapid expansion of tropical selective logging during the past 50 years with a wider range of species commercially exploited (Edwards *et al.* 2014). Now encompassing around half the permanent tropical forest estate (Blaser *et al.* 2011), selective logging is amongst the most widespread forms of anthropogenic disturbance in the tropics.

Conventional approaches to logging

Clear-cutting

Clear-cutting is probably the most common form of logging in boreal and temperate zones (Rosenvald and Lõhmus 2008; Kuuluvainen *et al.* 2012), and involves harvesting almost all tree cover in a single operation. Clear-cutting may be uniform across an area or carried out in smaller strips or patches, with operations ranging in extent from <1 hectare (ha) up to around 50 ha. Although small numbers of trees are often retained, the regenerating stand is predominantly even-aged, with silvicultural treatments (e.g. soil preparation, planting seeds or saplings) sometimes applied to facilitate regrowth. Clear-cutting also occurs in the tropics, but generally precedes conversion to different land uses (e.g. agriculture). Even tropical timber plantations are highly artificial systems relative to natural forest, and we therefore consider clear-cutting of tropical forest as land-use conversion and do not discuss this topic further.

Shelterwood cutting

Unlike clear-cutting, shelterwood forestry aims to maintain a continuous (partial) canopy cover throughout harvesting. Practised in some temperate deciduous forests (Brunet *et al.* 2010), this approach favours the regeneration of shade-tolerant species and involves an initial harvest of selected trees to thin the canopy, with further thinning guided by the light requirements of the desired regeneration. Some mature seed trees are retained through these thinnings, and when sufficient regeneration is achieved the remaining canopy is felled, resulting in a young, even-aged stand.

Selective logging

Selective logging is the most common form of timber extraction in the tropics, and involves harvesting all trees of commercially valuable species above specified diameter limits within a logging coupe. The volume of wood harvested varies substantially across the tropics depending on the density of marketable trees and the accessibility of the timber concession, with logging intensities typically highest in Southeast Asia and lower in South America and Africa (Putz *et al.* 2012).

Selective logging has been largely replaced by clear-cutting and shelterwood forestry in Eurasia and North America, although the potential for broader ecosystem benefits (e.g. aesthetic value, reduced soil erosion) has rekindled interest (Kuuluvainen *et al.* 2012). Operations can involve harvesting individual trees across the stand, or 'group selection' in which all trees from particular size classes are harvested from patches of forest and lower intensity thinning of the surrounding matrix takes place. Logging is often planned to retain trees from a range of size classes, with small-diameter trees dominating (Kuuluvainen *et al.* 2012). Unlike shelterwood systems, selective logging thus results in an uneven-aged stand, although both practices maintain a continuous canopy cover throughout.

Logging cycles

Forests managed for long-term wood production are intended to follow logging cycles – also termed rotations – in which trees are harvested and the forest is then left to regenerate for several decades before being relogged. These cycles ostensibly aim to maximise the volume of timber from each harvest without compromising future yields. In clear-cutting and shelterwood systems, regeneration must allow for growth from seed or sapling to optimal harvest age and so logging cycles are typically long (50–140 years, Brunet *et al.* 2010; Kuuluvainen *et al.* 2012). By contrast, selective logging in temperate and boreal forests involves much shorter cutting cycles, and may be viable with 20–30 year rotations (Kuuluvainen *et al.* 2012).

In the tropics, selective logging cycles of 30–60 years are typically proposed. However, the relatively recent advent of large-scale logging means that the long-term sustainability of these operations is uncertain. Furthermore, relogging sometimes takes place considerably earlier than originally intended (Edwards *et al.* 2014). To make early relogging economically viable, harvests of smaller trees are allowed, but despite removing large numbers of stems, timber yields are low and long-term harvest potential may be severely compromised (Putz *et al.* 2012). As the extent of unharvested tropical forest declines, repeated logging is likely to become increasingly common, and so an improved understanding of relogging impacts is central to successful long-term forest management and conservation.

Ecological impacts of logging

Forest structure and abiotic conditions

The immediate physical impacts of logging are most pronounced in clear-cutting: the loss of tree cover causes major changes to abiotic conditions (e.g. large increases in light levels, greater variability in temperature), and intensive machine use compacts the soil and breaks deadwood into small pieces (Brunet *et al.* 2010). Contemporary clear-cutting operations are sometimes accompanied by additional mechanical removal of deadwood and plant debris for safety reasons, to facilitate stand regeneration or, increasingly, as biofuel (Bouget *et al.* 2012), causing further damage to soil and residual vegetation. Without appropriate mitigation (see fourth section on mitigating the impacts of logging), regenerating stands can thus become highly homogenous in composition, age, and structure.

Shelterwood and selective logging systems have less pronounced physical impacts than clear-cutting, but changes can still be substantial. Conventional shelterwood management progressively opens up the canopy and ultimately results in relatively homogenous even-aged stands. Whilst selectively logged forest can maintain greater heterogeneity, forest structure nonetheless deteriorates as the largest, oldest trees are progressively harvested (Kuuluvainen *et* *al.* 2012). Shelterwood harvesting and selective logging also cause substantial mortality to non-target vegetation. In the tropics, felling and the construction of skid trails (corridors in the forest in which large vegetation is flattened to allow extraction of logs), logging roads, and logging decks can result in severe damage or mortality of 10–20 trees for every stem harvested (Feldpausch *et al.* 2005; Putz *et al.* 2008a), whilst in boreal and temperate forests, post-harvest mortality of residual trees from windthrow is problematic (Thorpe *et al.* 2008). Although shelterwood and selective logging systems aim to maintain continuous canopy cover, large gaps and canopy damage can thus result, leading to greater variability in soil and understory temperatures and increased light levels at the forest floor. Fast-growing understory plants and/or pioneer tree species are then favoured, often accompanied by dense tangles of lianas in tropical regions (Perry and Thill 2013; Edwards *et al.* 2014). Forest regrowth closes most canopy gaps within a few years, but recovery of mature forest structure can take far longer (Asner *et al.* 2004; Josefsson *et al.* 2010). Furthermore, in the most heavily impacted areas (e.g. frequently used skid trails), severe soil compaction combines with changes in microclimate to restrict regrowth to grassy, scrub-like vegetation for several years or even decades.

In addition to the smaller-scale changes in forest structure outlined above, at larger scales most selectively logged forests contain areas in which felling is limited by a lack of marketable trees or steepness, as well as parts subjected to very intensive harvesting. Large selective logging concessions thus encompass considerable variation in disturbance levels, sometimes including pockets of relatively intact forest. At wider spatial scales, differences in the timing of logging operations (for clear-cutting or for continuous cover forestry) usually also result in a mosaic of patches, each in a distinct stage of recovery from disturbance.

Biodiversity

The effects of logging on biodiversity are driven by shifts in forest structure and abiotic conditions and by the associated changes in resource availability. Impacts are most immediate following clear-cutting, in which short-term changes strongly favour species tolerant of open habitats (Graham-Sauvé *et al.* 2013). Where the conservation of early successional species is required, regenerating clear-cuts can thus provide valuable habitat – particularly if key structures typical of old-growth forest are retained (Perry and Thill 2013). Equally, however, the removal of most of the large, old trees and woody debris during clear-cutting causes declines amongst many birds and deadwood-dependent invertebrates, bryophytes, and fungi, whilst the major changes in microclimate regimes following canopy removal are detrimental to a range of forest specialists. In the absence of mitigation (see fourth section on mitigating the impacts of logging), the structurally homogeneous single-species stand typical of regenerating clear-cuts thus has limited value for many forest taxa, with several species groups taking decades to recover the composition found in mature forest (Paillet *et al.* 2010).

Through gradual harvesting and the maintenance of continuous canopy cover, shelterwood management has fewer immediate effects on forest taxa than clear-cutting (Graham-Sauvé *et al.* 2013), and has been proposed for situations where early successional forest is required but clear-cutting is considered problematic (Perry and Thill 2013). Nonetheless, conventional shelterwood systems still cause declines across a range of taxa (Brunet *et al.* 2010), particularly following the final harvest of seed trees. In the case of bryophytes and fungi, adverse effects of shelterwood management are caused by the removal of deadwood and by the hotter, drier microclimate that results from increased canopy openness. Similarly, many bird species typical of mature forest require structures for nesting and foraging that are rare in conventional shelterwoods (e.g. large, old trees and standing deadwood).

Total species richness in selectively logged forest is often very similar to that in unlogged forest, and in some instances may be higher in the former (Gibson *et al.* 2011; Graham-Sauvé *et al.* 2013; Figure 30.2). As with other logging practices, however, species richness patterns can mask significant changes in community composition, with generalist and disturbance-tolerant species increasing in abundance following logging whilst old-growth forest specialists decline. In tropical forests, for example, the dense post-logging understory vegetation adversely affects insectivorous bird and bat species that require an open understory for effective hunting (Peters *et al.* 2006; Edwards *et al.* 2011), whilst the combination of soil compaction and changes in temperature and humidity cause declines amongst soil-dwelling invertebrates (Vasconcelos *et al.* 2000; Jones *et al.* 2003). These changes in composition highlight the vulnerability of many tropical forest species to selective logging, although there is also evidence that the majority of species found in unlogged forest can persist despite intensive logging disturbance (Edwards *et al.* 2011; Woodcock *et al.* 2011), perhaps partly by surviving at lower densities in pockets of less degraded habitat.

In boreal and temperate forests, significant impacts of selective logging result particularly from the removal of large, old trees, which reduces nesting and foraging habitats in the short-term and limits the accumulation of deadwood in the longer-term (Abrego and Salcedo 2013). The latter changes can have detrimental impacts on deadwood-dependent taxa that persist for several decades (Josefsson *et al.* 2010). Equally, however, some forest taxa that decline following selective logging may recolonise relatively rapidly (Vanderkerkhove *et al.* 2011), highlighting the potential for selectively logged forest to contribute to biodiversity conservation.

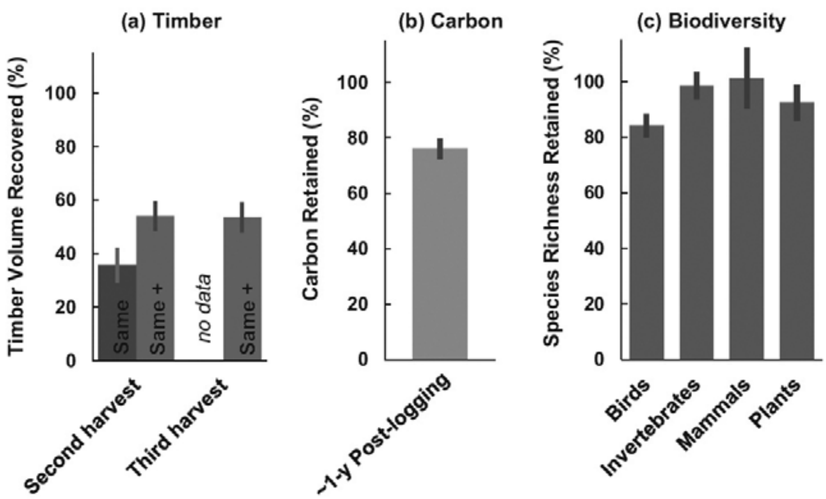

Figure 30.2 Results from meta-analysis examining the effects of tropical selective logging on (a) merchantable timber volume, (b) carbon stocks in living tree biomass approximately one year after logging, and (c) species richness in selectively logged forest as a percentage of that in old-growth forest. In (a), the volume harvested during the second and third cut is shown (cutting cycles 20–40 years). 'Same' refers to logging in which the same species are harvested, 'Same+' refers to logging in which additional species are harvested. Means and standard errors for (a), (b) and (c) are based on 59, 22 and 109 studies, respectively.

Source: Reproduced from Putz, F. E. *et al.* (2012), Sustaining conservation values in selectively logged tropical forests: the attained and the attainable, Conservation Letters, 5, 296–303, with permission from John Wiley and Sons. Copyright and Photocopying © 2012 Wiley Periodicals Inc.

Biotic interactions and ecological processes

Research on the ecological impacts of logging has generally focused on biodiversity metrics (e.g. species richness and composition), but logging disturbance can also alter key intra- and inter-specific interactions with implications for ecosystem functioning (Edwards *et al.* 2014). Perhaps the most extreme instances are major pest outbreaks in managed stands of boreal and temperate forests. Such outbreaks occur naturally in the relatively low diversity forests of these regions, and so may be exacerbated in systems managed for a small number of tree species with a homogenous age structure and reduced genetic variation (Rönnberg 2000; Wermelinger 2004). Similar factors may underlie increased infection rates by root rot fungi in trees damaged by logging (Rönnberg 2000).

Other changes in biotic interactions are sometimes inferred from shifts in the relative abundances of functional guilds (e.g. herbivores, frugivores, etc.). For example, meta-analysis of avian community responses to tropical selective logging identified insectivores and frugivores as being particularly vulnerable, suggesting that ecological processes such as seed dispersal and insect control may be affected by logging (Gray *et al.* 2007). Although relatively few studies have quantitatively compared ecological processes between unlogged and logged forest, there is evidence for reduced seed removal rates and shorter dispersal distances in logged tropical forest (Markl *et al.* 2012 and references therein, see also later section on the indirect effects of logging). Moreover, changes in biotic interactions can occur independently of shifts in species composition, as the ecology of individual species shifts in response to disturbance (Edwards *et al.* 2013; Woodcock *et al.* 2013).

Carbon stocks

Forests are increasingly recognised as an important global carbon sink, and so understanding and mitigating the effects of logging on forest carbon stocks represents a key aspect of strategies to combat climate change. This section focuses on changes in forest carbon, but note that from a carbon accounting perspective, the fate of timber products will differ amongst forest types and influence net CO_2 emissions from logging.

Clear-cutting operations remove almost all aboveground vegetation, and therefore cause a major reduction in carbon stocks. Some carbon is retained in remaining deadwood, although, because fallen branches decay quickly, this pool is rapidly depleted. Accumulation of carbon occurs slowly as the forest regenerates, and can take up to 200 years or longer to reach pre-logging levels (Holtsmark 2012). Planting multi-species mixtures of deciduous species rather than single-species coniferous stands can accelerate the recovery of carbon stocks, because the former has faster rates of biomass production (Figure 30.3; Gamfeldt *et al.* 2013).

Selective logging reduces tropical forest carbon stocks through the direct removal of timber. However, decomposition of the large volumes of non-target vegetation damaged during felling combined with vegetation clearance for logging infrastructure (skid trails, logging decks) generally has the larger impact (Pearson *et al.* 2014). On average, carbon stocks are 24 per cent lower in selectively logged forest, with considerable variation reflecting differences in logging intensity and harvest methods (Figure 30.4; Putz *et al.* 2008a; Putz *et al.* 2012). Post-logging carbon accumulation can be rapid (Gourlet-Fleury *et al.* 2013; Edwards *et al.* 2014), and although recovery of carbon stocks to primary forest levels may take several decades, regenerating selectively logged tropical forests provide a substantial carbon sink – particularly when contrasted with alternative land uses such as agricultural plantations (Edwards *et al.* 2014). Repeated logging without appropriate regeneration periods

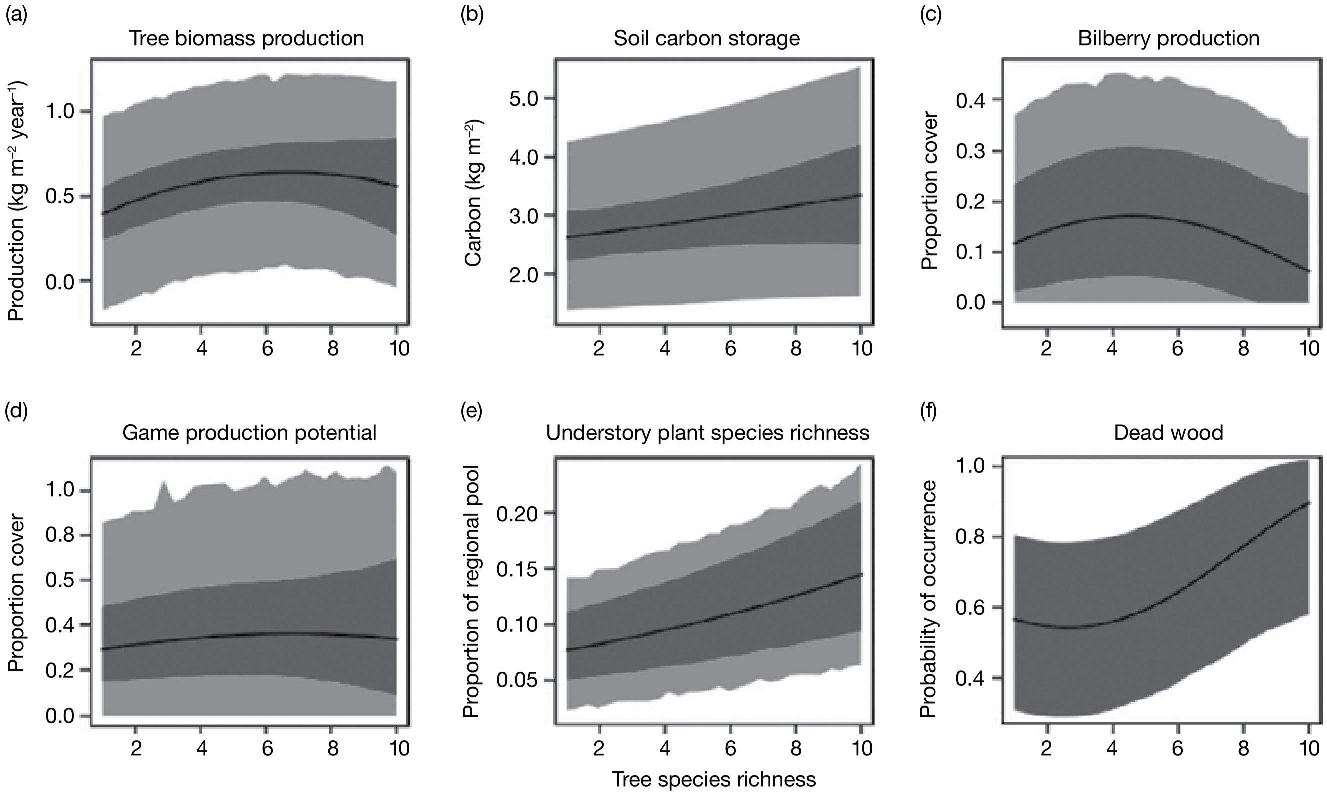

Figure 30.3 Relationships between tree species richness and ecosystem services in boreal and temperate production forests. Ecosystem services are (a) tree biomass production, (b) soil carbon storage, (c) bilberry production, (d) game production potential, (e) understory plant species richness, (f) occurrence of dead wood. Mean relationships (black) are shown, with 95 per cent confidence intervals for the relationships excluding (dark grey) and including (light grey) the residual variation

Source: Figure and legend text reproduced from Gamfeldt *et al*. (2013) *Nature Communications*, 4, 1340. doi:10.1038/ncomms2328 (with permission).

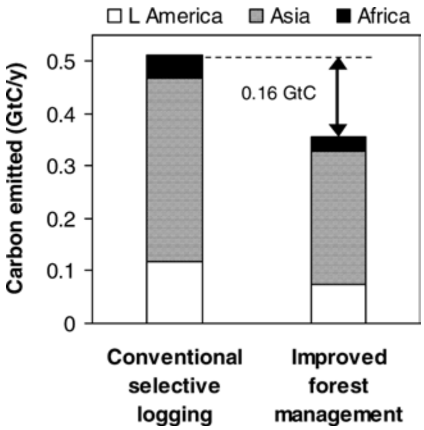

Figure 30.4 Estimated annual reduction in global carbon emissions that would result from improved forest management

Source: Figure and legend text reproduced from Putz *et al.* (2008a) *PLoS Biology*, 6(7), e166. doi:10.1371/journal.pbio.0060166 (with permission).

may erode carbon stocks, however, and recovery within relogged forest has received relatively little attention (Putz *et al.* 2012).

Indirect effects of logging

Logging operations are associated with a number of generic anthropogenic impacts. Perhaps the most pervasive of these indirect effects stems from the construction of networks of logging roads for transporting timber. In Central Africa, for example, Laporte *et al.* (2007) documented rapid expansion in road-building within timber concessions, and conservatively estimated >50,000 km of logging roads in the region, whilst an estimated 250,000 km of logging roads were constructed in Borneo from 1973–2013 (Gaveau *et al.* 2014). Roads make previously remote areas accessible, resulting in increased hunting pressure and greater risk of complete forest clearance (Asner *et al.* 2006; Edwards *et al.* 2014). Logged tropical forests can also be more susceptible to further degradation through fires, as a consequence of the hotter drier conditions and large volumes of debris from non-target vegetation (Asner *et al.* 2006).

Mitigating the impacts of logging

Approaches to mitigating the impacts of logging by modifying forestry practices can be divided into actions that take place before or during logging, and those that occur post-logging.

Mitigation before and during logging

Close-to-nature forestry

Developed and applied in Europe and North America (and also known variously as ‘back-to-nature forestry’, ‘near-to-nature forestry’, ’nature-based silviculture’, ‘natural disturbance based forest management’, ‘emulating natural disturbance regimes’ or ‘ecological silviculture’), close-to-nature forestry seeks to maintain wood production with less detrimental impacts on biodiversity and wider ecosystem values than conventional logging. 'Nature' in this context is defined either as restoring forest structure and composition to a reference state (e.g. unlogged forest) or using forestry interventions that mimic processes occurring within natural forest (Gamborg and Larsen 2003; Long 2009): both approaches therefore move away from intensively managed monocultures and conventional clear-cutting.

A suite of practices can be considered aspects of close-to-nature forestry, including maintaining a continuous canopy cover, maintaining mixed-species stands of native trees, using natural regeneration, retaining deadwood and standing dead trees, and minimising the use of fertilisers and pesticides (Gamborg and Larsen 2003). These practices buffer forests against climate extremes and help species typical of old-growth forest to persist. Equally, however, maintaining wood production necessitates harvesting commercially valuable large, old trees together with some deadwood removal (Gossner *et al.* 2013). The ecological impacts of close-to-nature forestry therefore fall on a continuum between more conventional logging and strict forest protection (Gamborg and Larsen 2003).

Retention forestry

Retention forestry focuses on maintaining structures that are important for biodiversity and ecological processes but that are typically lost during conventional logging. Originally developed in North America, the practice is most commonly applied in boreal and temperate forests managed using clear-cutting, although the relevance of retention forestry for other systems is increasingly recognised (Gustafsson *et al.* 2012; Lindenmayer *et al.* 2012). The structures retained encompass features that are rare and/or take a long time to develop, and may include pieces of deadwood, individual trees (often above a minimum diameter), or small patches of unharvested forest (Figure 30.5). Retention of these structures may be aggregated or dispersed across the landscape, with a minimum of 5–10 per cent of the total volume of the stand recommended (Gustafsson *et al.* 2012).

Retention forestry can buffer against more extreme changes in microclimate and provide a 'lifeboat' to allow old-growth forest species to persist following clear-cutting, whilst areas of intact forest also act as stepping stones or corridors for dispersal between mature stands. These effects increase species richness and abundance for some taxa (e.g. birds, ectomycorrhizal fungi, beetles). Benefits for other groups (e.g. bryophytes) are less clear, however, and syntheses are complicated by variation amongst studies in the volume, type and distribution of structures retained (Rosenvald and Lõhmus 2008).

The concept of Woodland Key Habitats (WKH) is closely related to retention forestry, and applied most prominently in northern Europe. WKH are selected based on edaphic conditions, hydrology or geomorphology, or following the identification of key structural features such as late successional forest, riparian forest, aggregations of logs, and forest springs. These habitat patches are then either excluded from logging or logged at lower intensities (Timonen *et al.* 2012). Similar networks of key habitats are also retained in other regions – e.g. in North America, relatively wide riparian buffer strips are often protected to conserve aquatic and terrestrial biota (Marczak *et al* 2010). Where WKH or similar patches are incorporated strategically into a reserve network, connectivity between habitats can be enhanced, although small and isolated WKH have more limited biodiversity benefits, particularly for taxa with short dispersal capabilities (Laita *et al.* 2010).

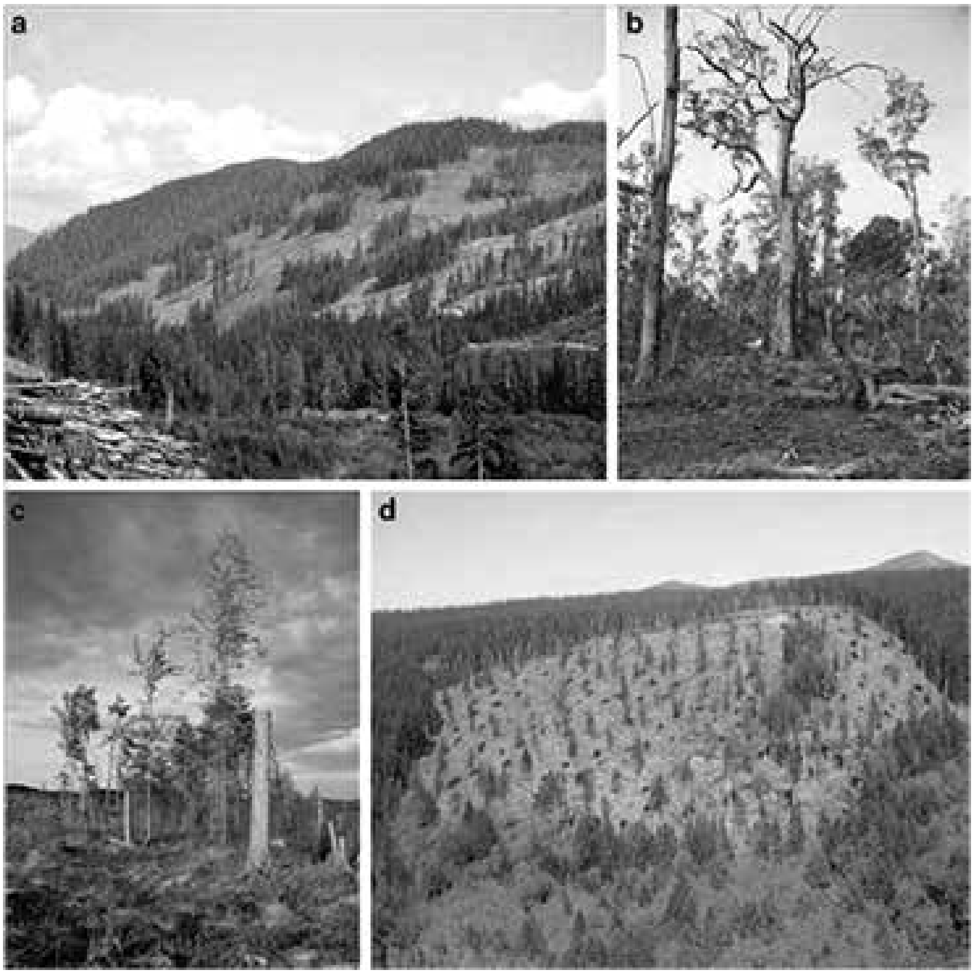

Figure 30.5 Retention forestry in different parts of the world: (a) Group retention in coastal Canada, (b) Tree and habitat retention in a gap release treatment in Western Australia, (c) Small aggregate and created dead wood in boreal Sweden, (d) Dispersed retention in Washington State

Source: Reproduced from Gustafsson *et al.* (2012), Retention forestry to maintain multifunctional forests: a world perspective, *BioScience*, 62, 633–645, with permission from Oxford University Press on behalf of the American Institute of Biological Sciences.

Reduced Impact Logging

Reduced Impact Logging (RIL) is applied in tropical forests as an alternative to conventional selective logging (CL), and encompasses several practices that are intended primarily to improve the long-term sustainability of timber harvesting (Putz *et al.* 2008a). The practices employed vary but include one or more of the following: (1) a full inventory and mapping prior to logging; (2) planning and restrictions on skid trails, logging roads, and log decks to avoid unnecessary construction; and (3) pre-harvest liana cutting and directional felling to minimise damage to non-target vegetation (Putz *et al.* 2008b).

RIL is most effective at mitigating logging impacts that are related to forest regeneration. By combining planned extraction routes with directional felling, residual damage can be decreased by 50 per cent relative to CL (Putz *et al.* 2008a). Pre-harvest liana cutting further reduces damage to non-target trees, as well as benefitting regenerating forest by restricting liana densities post-logging (Alvira *et al.* 2004). Appropriately practised, RIL thus allows logged forest to maintain a more similar forest structure to unlogged forest, with significantly less canopy damage (Asner *et al.* 2004). RIL forest may also retain higher carbon stocks than CL forest (Figure 30.4; Putz *et al.* 2008a), although the benefits of RIL for minimising CO_2 emissions are highly dependent on the particular suite of measures applied (Griscom *et al.* 2014).

Relatively few studies have examined the extent to which RIL mitigates the direct effects of logging on biodiversity, and whilst there is some evidence for higher species richness in RIL versus CL forest, other studies found no difference between forest types (see Edwards *et al.* 2012 and references therein). Moreover, the benefits of RIL for biodiversity reflect the intensity and type of practices employed, and there is a need for more targeted research in this respect. For example, pre-felling planning to reduce the number of skid trails may be particularly important in limiting access by poachers, and also results in less vegetation clearance. Similarly, practices that maintain a more intact canopy structure may reduce fire risk, whilst improved long-term timber yields from more sustainable management could provide greater economic and political incentives for forest retention over conversion.

Mitigation post-logging

Post-logging mitigation measures generally seek to (1) maintain future timber yields and/or (2) assist the recovery of logged forest back towards the natural state ('ecological restoration'; SER 2004). Whilst these objectives overlap, they are not necessarily identical. Silvicultural treatments designed to maintain timber yields involve the removal of lianas and understorey vegetation (liberation cutting), combined with planting saplings of commercial species (enrichment planting). These treatments enhance forest regeneration and carbon sequestration relative to naturally regenerating forest (Gourlet-Fleury *et al.* 2013), and can have positive effects on biodiversity. For example, insectivorous bird species that decline following logging benefit from the more open understorey that results from liberation cutting and enrichment planting (Ansell *et al.* 2011).

Ecological restoration can include the silvicultural techniques described above, and may involve major ecosystem modifications such as reforesting cleared areas and utilising prescribed fires (Suding 2011; Halme *et al.* 2013). More subtle measures are also sometimes employed, such as creating deadwood and small gaps, and blocking ditches (Halme *et al.* 2013). In the short-term, ecological restoration can benefit target groups (e.g. species dependent on fires or on deadwood), provided these groups are able to colonise the restored sites. More permanent benefits of restoration are less certain, however, reflecting the temporary nature of some techniques and the need for longer-term research (Kouki *et al.* 2012; Komonen *et al.* 2014).

Conclusion

Logging operations encompass a wide range of practices and mitigation strategies, and cannot be regarded as having a single, globally consistent set of effects. The picture is further complicated by the lack of long-term (i.e. decadal) data on the impacts of repeated logging, and by inherent differences between ecosystems. Nonetheless, some general patterns emerge. The impacts of clear-cutting on habitat structure, carbon stocks, and biodiversity are more severe than the impacts of selective logging, and for both practices, mitigation measures can alleviate negative effects to some extent. There is also increasing recognition of the potential conservation significance of permanent production forest, with selective logging (in particular) apparently less detrimental to biodiversity than other forms of anthropogenic disturbance (e.g. complete forest clearance for agriculture; Gibson *et al*. 2011; Edwards *et al*. 2014) and mitigation measures such as retention forestry proposed to allow more sustainable management (Lindenmayer *et al*. 2012). Whilst production forests should not be viewed as a substitute for unlogged, old-growth forest, the value of well-managed logged forest as a complement to strictly protected areas should not be ignored, particularly in regions where the conservation of extensive areas of pristine habitat is no longer possible, or is economically or socially unfeasible.

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