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The relationship between biodiversity, carbon storage and the provision of other ecosystem services

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Acronyms and abbreviations

ANR	Assisted natural regeneration
CBFF	Congo Basin Forest Fund
CO_2e	Carbon dioxide equivalent
DECC	UK Department of Energy and Climate Change
Defra	UK Department for Environment, Food and Rural Affairs
DFID	UK Department for International Development
ES	Ecosystem service
FAO	Forestry and Agriculture Organisation
FCPF	Forest Carbon Partnership Facility
FGMC	Forest Governance, Markets and Climate Programme
FIP	Forest Investment Programme
GDP	Gross domestic product
GHG	Greenhouse gas
Ha	Hectare
HIV/AIDS	Human immunodeficiency virus infection / acquired immunodeficiency syndrome
ICF	International Climate Fund
IUCN	International Union for Conservation of Nature
IUFRO	International Union of Forest Research Organisations
JFM	Joint forest management
KPI	Key performance indicator
Lao PDR	Lao People's Democratic Republic
LCD	Low carbon development
MA	Millennium Ecosystem Assessment
MDB	Multilateral development banks
MW	Megawatt
NTFP	Non timber forest product
PA	Protected Area
PES	Payments for ecosystem services
REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries, including the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks.
t	ton
RIL	Reduced impact logging
RMB	Renminbi (Chinese yuan)
TEEB	The Economics of Ecosystems and Biodiversity
UK NEA	UK National Ecosystem Assessment
UN	United Nations
UNEP-WCMC	United nations Environment Programme World Conservation Monitoring Centre
WWF	Worldwide Fund for Nature

Executive Summary

This review of the relationship between biodiversity, carbon storage and the provision of other ecosystem services in tropical forests was carried out by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) for the United Kingdom Department for International Development (DFID). The study provides general lessons around the role of biodiversity in generating, maintaining and/or enhancing ecosystem services relevant to the International Climate Fund (ICF), as well as related guidance relevant to specific types of interventions.

This report details the findings of a critical literature review of relevant papers, as well as lessons related to the design of investments under the forestry components of the ICF. In summarising the evidence, estimates of overall confidence of the linkage between biodiversity and the ecosystem services of interest have been made, based on the UK National Ecosystem Assessment confidence descriptions (UK NEA, 2011). These are, in order of strength: '**Well established**', '**established but incomplete evidence**'; '**competing explanations**'; and '**speculative**'; (see Introduction for more detail).

Box 1: Key terms

Biodiversity *The diversity of living organisms at the genetic, species, and ecosystem scales; this review considers multiple aspects of biodiversity (including species richness, composition, and community structure, presence and abundance of individual species, presence of particular ecosystems and ecosystem intactness) in order to capture its full breadth.*

Ecosystem Services The benefits (*goods and services) provided by ecosystems that contribute to human wellbeing.*

Resilience *The ability of a system or stock to persist, grow, adapt, and recover in the face of environmental shocks and disturbances.*

Evidence has been reviewed for the relationships between biodiversity and the following ecosystem services:

- Climate regulation, i.e. carbon stocks and their resilience;
- Other regulating services, including soil fertility and erosion control , water regulation and quality, protection from natural hazards and climate regulation;
- Provisioning services, including timber, fuelwood, food and medicine.

The final section of the report discusses lessons from the review for the forestry component of the ICF and outlines the trade-offs and synergies for particular interventions that might form the basis of ICF investments.

Key findings

Forests provide a range of provisioning, regulating, supporting and cultural ecosystem services that are important not only locally, but also globally. It is clear that biodiversity in tropical forests plays a role in supporting the provision of ecosystem services in that without any biodiversity, there would be for example, no carbon sequestration, no pollination or other ecosystem services. What is less clear is the type and strength of the relationships between increasing numbers of species, or other aspects of biodiversity, and the delivery of ecosystem services.

Carbon storage and sequestration

Globally there is a generally positive relationship between carbon stocks and biodiversity; tropical moist forests are rich in both. However, within intact tropical forests the patterns are more complex and there is no clear evidence for a correlation between spatial patterns of carbon stocks and biodiversity.

Whether and to what degree biodiversity influences carbon stocks in tropical forests is still uncertain, although experimental work in other ecosystems has shown that biodiversity often promotes stability and primary productivity, and therefore carbon stocks. Ecological theory and grassland experiments suggest a potential link between biodiversity (in terms of species richness) and ecosystem functioning; however, conclusions from experimental ecosystems may not hold true for much more species-rich systems such as tropical forests.

There is *established but incomplete evidence* supporting the link between species richness (and diversity) and forest carbon sequestration. Increased species richness has been shown to increase sequestration, both due to the increased chance of having highly productive species present (a sampling effect) and due to the more efficient use of resources that results from the presence of multiple species with different requirements (a complementarity effect).

Turning to resilience of carbon stocks, it is *well established*, with strong theoretical as well as empirical support, that biodiversity confers resilience to some types of ecosystems. It is also *well established* that carbon stocks in intact forests are more resilient than those in degraded or fragmented forest. There is clear experimental and observational evidence in tropical forest that large contiguous forest areas are more resilient than smaller patches. Preserving more natural forests (e.g similar in species composition to undisturbed forests) will promote resilience by decreasing their recovery times after climate-related disturbances such as, fires and droughts.

Other regulating services

In addition to climate regulation through carbon storage, forests provide a range of regulating ecosystem services that are important both globally and locally. Stronger evidence was found for the role that natural, intact forests play in providing regulating services than for differences in service provision with species richness within those forests. For example, this review has found *established but incomplete evidence* for the link between the biodiversity and the primary productivity of ecosystems, and that different management regimes can influence the relationship between biodiversity and the productivity of forests.

This review highlights a *well established* link between intact forest cover and the reduction of soil erosion. There is also *established but incomplete evidence* of a link between forest cover and soil fertility, and *established but incomplete evidence* of the link between biodiversity (in terms of species richness, vegetation presence and type) and reduced loss of soil nutrients.

A *well established* link exists between biodiversity (in terms of individual species, species richness and abundance) and pollination services. Although a range of different species and groups (including insects, birds and mammals) are important for the dispersal of seeds the evidence found that increased levels of biodiversity enhance the dispersal of seeds was only *speculative*. *Established but incomplete evidence* was found in this review for the link between mangroves and productivity in fisheries: the presence of mangroves has been shown to enhance the number of species caught and income from catches in offshore fisheries.

The *evidence* regarding the link between biodiversity and human disease prevention *is speculative*, largely based on the *established but incomplete evidence* supporting a link between biodiversity and animal and plant disease prevention. The presence of forest is associated with a reduced incidence of avian malaria, while deforestation increases it. However, a *well established* link exists between biodiversity, (in terms of species richness, connectivity to forests and tree cover), and biological control of pests and diseases of crops.

This review highlights a *well established* link between the presence and intactness of forest ecosystems and water regulation and quality. *Established but incomplete evidence* was also found supporting the link between the presence of forest ecosystems and damage from natural hazards, and between forest ecosystems and climatic and microclimatic regulation.

Box 2: Key Issues to consider

Proximity Different kinds of ecosystem services have different spatial relationships with their beneficiaries. For example, some ecosystem services are supplied at the global level (e.g. atmospheric carbon regulation), while others are supplied via beneficiaries in direct contact with the ecosystem (e.g. provision of medicinal plants). In general regulating services can be supplied at greater distances from their beneficiaries than provisioning services.

Access Even where ecosystems have high potential to provide services, access to the ecosystem strongly mediates the extent to which these services are taken up by beneficiaries. This is particularly true for ecosystem services that require direct contact with the source ecosystem (i.e. provisioning services). If a particular intervention increases the potential for supplying ecosystem services, but reduces levels of access, the net flow of ecosystem services to humans will be reduced in the immediate future.

Disturbance The use of many ecosystem services, especially provisioning services, entails disturbance of the system that can in turn affect the supply of a range of ecosystem services. For example, depending on the harvest regime, timber extraction may affect both future supplies of timber and fuelwood, as well as hydrological and other services provided by the forest. Some species and ecosystems can sustain heavier pressure than others, and biodiversity may confer resilience through differential responses. However, there is a significant risk that use of one ecosystem service can, through disturbance and/or unsustainable harvest, affect its long term supply and that of other services.

Provisioning services

Forests provide timber and non-timber forest products (NTFPs) to both local and more distant beneficiaries.

Timber

It is *well established* that pristine forests are the major sources of many tropical timber species, and there is some evidence showing that more species rich forests are more important for timber production.

Non-timber forest products

- **Food**

It is *well established* that foods from forest ecosystems play a vital role in supporting the livelihoods and wellbeing of people in many tropical countries. It is also *well established* that wild foods can be used to diversify both the diet and livelihoods of rural communities and that biodiversity plays an important role in maintaining food security. It is *well established* that intact forest ecosystems can provide a greater availability of food products than secondary or degraded forests, but impacts on abundance varies between species.

- **Fodder**

It is *well established* that wild plants are crucial for feeding and maintaining livestock, and that a wide range of species are important in providing fodder for the livestock of rural communities.

- **Medicinal products**

It is *well established* that tropical forests provide a major contribution to the healthcare needs of indigenous and rural communities and for the development of conventional medicines, and are also important for supporting livelihoods It is also *well established* that many people living in rural areas of developing countries are dependent on medicinal plants for their main source of healthcare, and that a large number of species play a key role in delivering medicinal plant services. Furthermore, findings from the review suggest that where multiple plants are used for the same health issues, higher biodiversity may ensure continued supply of this service, enhancing people's resilience in the face of environmental change. It is *well established* that secondary forests and disturbed habitats provide considerable quantities of medicinal plants. Accessibility, cultural practices and perceptions are also important to the choices made by medicinal plant users. Traditional knowledge is a vital component of medicinal ecosystem services.

- **Fuelwood**

Wood is the major source of energy for rural communities in many tropical regions, particularly in sub-Saharan Africa. It is *well established* that pristine forests, degraded forests and areas outside forests are all important sources of fuelwood. A wide range of trees are used as fuelwood, and there is *speculative evidence* that native tree species are more important as fuelwood than exotic species. The wide range of fuelwood species means that a forest with high species richness can provide valuable livelihood benefits for communities, even if the most valuable timber species have been exhausted.

The review has found that there are *competing explanations* regarding the severity of the impacts of fuelwood collection on biodiversity and the provision of other ecosystem services. The literature suggests measures such as the improved management of forests and woodlands, fuel efficient stoves, and the planting of fuelwood species to prevent the loss of fuelwood resources.

Summary of lessons

The findings of this review provide lessons for the forestry component of the ICF, with implications for selection and design of interventions in tropical forests (specific considerations related to types of interventions in the forestry sector are examined in Annex 3). The broader lessons from the review include the following:

Biodiversity and its conservation have value beyond a 'side benefit' of forestry interventions; biodiversity is important in delivering a range of ecosystem services and in maximising the achievement of the primary objectives of the ICF. If safeguarding biodiversity is thus considered to be a priority objective of future ICF interventions, then it should also be measured and monitored explicitly.

Aspects of biodiversity can also reasonably be considered as important to the adaptation and resilience component of the ICF. The findings of the review suggest that intactness and naturalness in tropical forests, as well as the redundancy provided by a diversity of biological resources, confers a greater degree of resilience to environmental change and stress (including to climate change), both for ecosystems and the communities that rely on them.

Measures to conserve intact, natural forest, and to restore degraded areas to near natural levels of intactness and diversity, are likely to be broadly effective at preserving carbon storage and other ecosystem services that benefit local populations (subject to issues of access and use rights).

The carbon storage, biodiversity and ecosystem service benefits of forests are best understood at the landscape level, and forestry interventions are best planned at the landscape level, in order to maximise the synergies between different objectives and to minimise risks (such as displacement or leakage).

The use of biodiversity by communities is often associated with particular types of knowledge, cultural practices and preferences. Interventions aimed at enhancing the benefits to livelihoods and the sustainability of ecosystem services should therefore recognise and make use of the role played by traditional and community knowledge and practices.

There is scope for a more in-depth review of the practical experiences gained through the implementation of interventions in tropical forests and factors potentially linked to the success of interventions. This may contribute to the development of guidance to support decision-making about the choice of interventions and implementation approaches in particular locations.

Introduction

Context

This review of the relationship between biodiversity, carbon storage and the provision of other ecosystem services was carried out by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) for the United Kingdom Department for International Development (DFID). The purpose of this study is to undertake a critical review focusing on tropical forests, to provide more specific conclusions and policy guidance around the role of biodiversity in generating, maintaining and/or enhancing other ecosystem services relevant to the International Climate Fund (ICF).

Our knowledge of the link between the diversity of species within an ecosystem and the supply of ecosystem services is increasing, although this relationship is not fully understood. Generic examinations of this issue, through initiatives such as the Millennium Ecosystem Assessment (MA, 2005a), the Economics of Ecosystems and Biodiversity (TEEB) (Kumar, 2010), the UK National Ecosystem Assessment (UK NEA, 2011) and scientific reviews (e.g. Cardinale et al., 2012) have developed broad conclusions that biodiversity generally has a positive relationship with the level, or quality, and long term provision of ecosystem services. However, the nature and strength of the relationships between biodiversity and ecosystem services remain unclear.

Understanding the ecological relationships between the presence of biodiversity and the other ecosystem service benefits we wish to maintain or enhance is therefore crucial if we are to deliver long term benefits to local people, address global climate change and support biodiversity conservation objectives – it will help inform decisions around the type, scale and methods we apply to protect and manage forests.

Objectives

The objectives of this review are as follows:

- Focussing on tropical forests, based on a critical review of research and building on existing research syntheses, provide more specific conclusions and policy guidance around the role of biodiversity in generating/maintaining/enhancing other ecosystem services relevant to the objectives of the forestry components of the ICF.
- In addition to drawing conclusions on the relationship between biodiversity, carbon storage and other ecosystem services in tropical forests as a whole, highlight evidence in relation to particular regions, forest types, management regimes or conservation status of biodiversity.
- Identify lessons to help inform the strategy of investment under the forestry component of the ICF; include lessons that will help project and programme managers seek out investments with multiple positive long term benefits for carbon storage, biodiversity and human wellbeing, with a focus on the potential for synergies or trade-offs between policy objectives.

The International Climate Fund

The International Climate Fund (ICF) was established by the UK Government in 2011 to support international poverty reduction by helping developing countries to adapt to climate change, take up low carbon growth, and tackle deforestation (UK Department of Energy and Climate Change (DECC), 2011). The ICF will provide £3.87 billion of climate finance from within the existing UK aid budget from 2011 to 2016 (DECC, 2013), allocated between adaptation (50%), low carbon development (30%) and forestry (20%). According to DECC (2011), ICF resources will be used to:

- Build global knowledge and evidence that low carbon, climate resilient development, including REDD+, supports growth and reduces poverty.
- Develop, pilot and scale up low carbon, climate resilient programmes and approaches to reduce emissions, support adaptation and protect forests, including biodiversity.
- Support country level action on low carbon, climate resilient development, including REDD+.
- Build an enabling environment for private sector investment and to engage the private sector to leverage finance and deliver action on the ground.
- Mainstream climate change into UK overseas development assistance, European Union development assistance and multilateral development bank (MDB) lending.

The forestry component of the ICF centres on the assumption that "Tackling deforestation offers big opportunities to reduce poverty, reduce emissions and protect biodiversity" (DECC, 2011). Based on an independent review of opportunities for scaling up UK reducing emissions from deforestation and forest degradation in developing countries (REDD+) finance, the ICF forestry component continues to support multilateral initiatives, as well as bilateral engagement, for reducing deforestation, such as forest law enforcement, governance and trade (FLEGT) and REDD+. Initiatives currently supported by ICF related to forestry include[1]: the Forest Investment Programme (FIP), administered by the World Bank; the Forest Carbon Partnership Facility, administered by the World Bank; the BioCarbon Fund, also administered by the World Bank; the Congo Basin Forest Fund (CBFF), administered by the African Development Bank; the UK Forest Governance, Markets and Climate (FGMC) programme; the Forestry Knowledge and Tools (KnowFor) initiative; and bilateral cooperation in Brazil, Nepal, Colombia and Indonesia.

The ICF Key Performance Indicators (KPIs) are used to measure and monitor the results of its programmes, and are shown below in Table 1. In addition, according to DECC (2011), all ICF programmes will be required to consider impacts on biodiversity and the wider environment.

Table 1: ICF Key Performance Indicators (source: Summary of Key Performance Indicators, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/253682/ICF-KPI-summary.pdf)

[1] Information on initiatives from publicly available ICF material, such as: DECC (2013) and https://www.gov.uk/government/policies/taking-international-action-to-mitigate-climate-change/supporting-pages/reducing-emissions-from-deforestation-and-forest-degradation-redd

Theme	Indicator	Unit
Adaptation	Numbers of people supported by ICF programmes to cope with the effects of climate change	Number of people
Adaptation	Number of people with improved resilience as a result of ICF support	Number of people
Low carbon development (LCD)	Number of people with improved access to clean energy as a result of ICF programmes	Number of people
LCD	Level of installed capacity of clean energy as a result of ICF support	MW
LCD	Number of low carbon technologies supported (units installed) through ICF support	Absolute units
Forestry	Number of forest dependent people with livelihoods benefits protected or improved as a result of ICF support	Number of people
Forestry	Value of ecosystem services generated or protected as a result of ICF support	---
Forestry	Number of hectares where deforestation and degradation have been avoided through ICF support	Ha
Cross cutting	Number of direct jobs created as a result of ICF support	Number of people
Cross-cutting	Change in Greenhouse Gas (GHG) emissions as a result of ICF support	tCO2e
Cross-cutting	Volume of public finance mobilised for climate change purposes as a result of ICF funding	£ legally committed in the 12 month period
Cross-cutting	Volume of private finance mobilised for climate change purposes as a result of ICF funding	£ legally committed in the 12 month period
Cross-cutting	Level of integration of climate change in national planning as a result of ICF support	Overall score (0 to 10) and individual question scores (0, 1, 2)
Cross-cutting	Level of institutional knowledge of climate change issues as a result of ICF support	Overall score (0 to 10) and individual question scores (0, 1, 2)
Cross-cutting	Extent to which ICF intervention is likely to have a transformational impact	Score 1 to 4

Biodiversity and ecosystem services

Biodiversity is defined by Convention on Biological Diversity (CBD) as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems"* (UN, 1992). This definition highlights the different aspects and levels of organisation that are encompassed by the concept of biodiversity. As noted by the Millennium Ecosystem Assessment (MA, 2005b), biodiversity refers to diversity at multiple scales of biological organisation (including genes, populations, species, and ecosystems) and can be considered at any geographic scale (such as local, regional, or global).

This review considers evidence related to multiple aspects of biodiversity, such as species richness, composition, structure, functional diversity[2], presence and abundance of individual species, presence of particular ecosystems and ecosystem intactness, in order to capture the breadth of its value and links to ecosystem services. For example, species richness may be valuable because a variety of species increases the resilience of an ecosystem, while an individual component of biodiversity (such as a particular plant species) may be valuable as a biological resource (MA, 2005b).

Ecosystem services are defined as the benefits that people obtain from ecosystems (MA, 2005a), and this review follows the approach developed by the MA, which classifies ecosystem services into four main categories: provisioning, regulating, supporting, and cultural services (see figure 2 below). The ecosystem services falling within these four categories play different roles in their support of human well-being, which can be broken down into the constituents set out by the MA: security (such as security from disasters); basic materials needed for a good quality of life (such as sufficient food and shelter); health (such as access to clean water and air); social relations (such as social cohesion); and freedom of choice and action (opportunities to achieve what is valued by an individual or community). For example, provisioning services have a clear link to supporting people's livelihoods and food security, while regulating services, such as climate and water regulation play a role in supporting livelihoods as well as health and security.

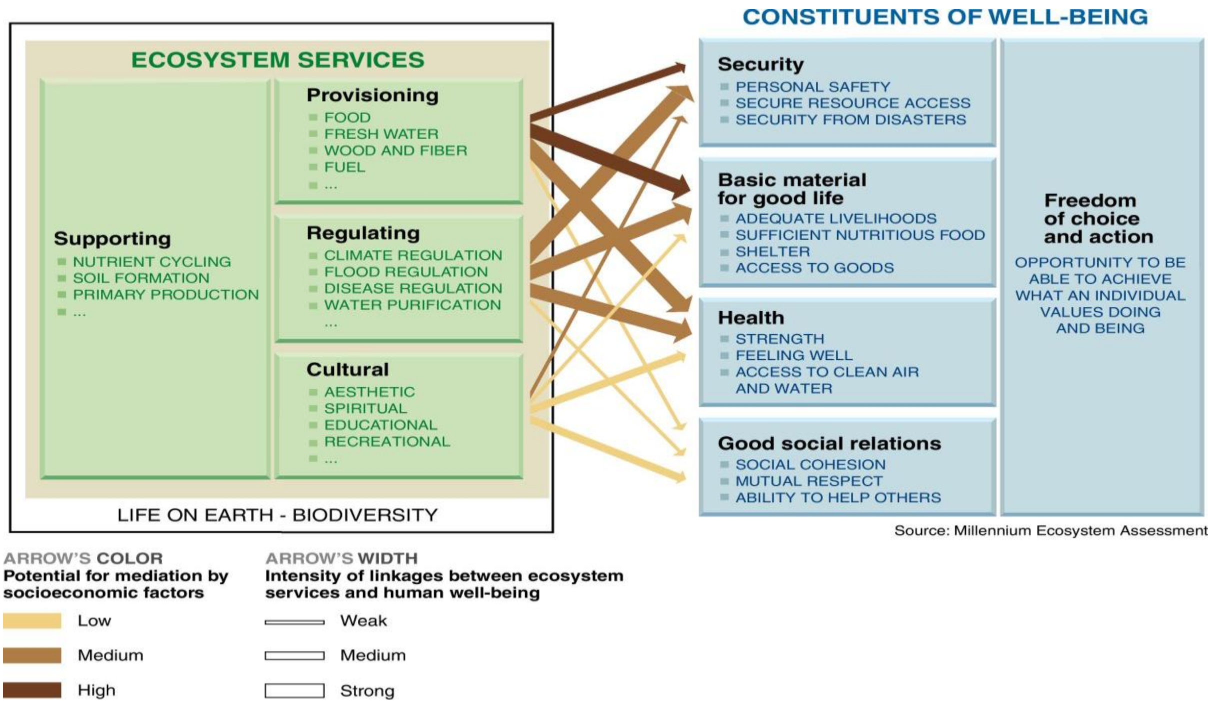

Figure 1: Ecosystem services and their role in supporting human well-being (MA, 2005b)

For the purposes of this review, we have prioritised examination of the relationship between biodiversity and certain ecosystem services most relevant to tropical forests and the priorities of the ICF: the regulating service of carbon storage and the resilience of carbon stocks; other regulating services (e.g. soil fertility, climate regulation and pollination services) and provisioning services (e.g. food and timber), particularly those services with local beneficiaries. In attempting to understand

[2] Functional diversity is defined by Diaz Díazand Cabido (2001) as "the value and range of functional traits of the organisms present

the relationships and interactions between biodiversity and these ecosystem services, it is also important to consider the aspects of biodiversity discussed above (such as species richness and composition) and how these are expressed through ecosystem functions (see figure 3).

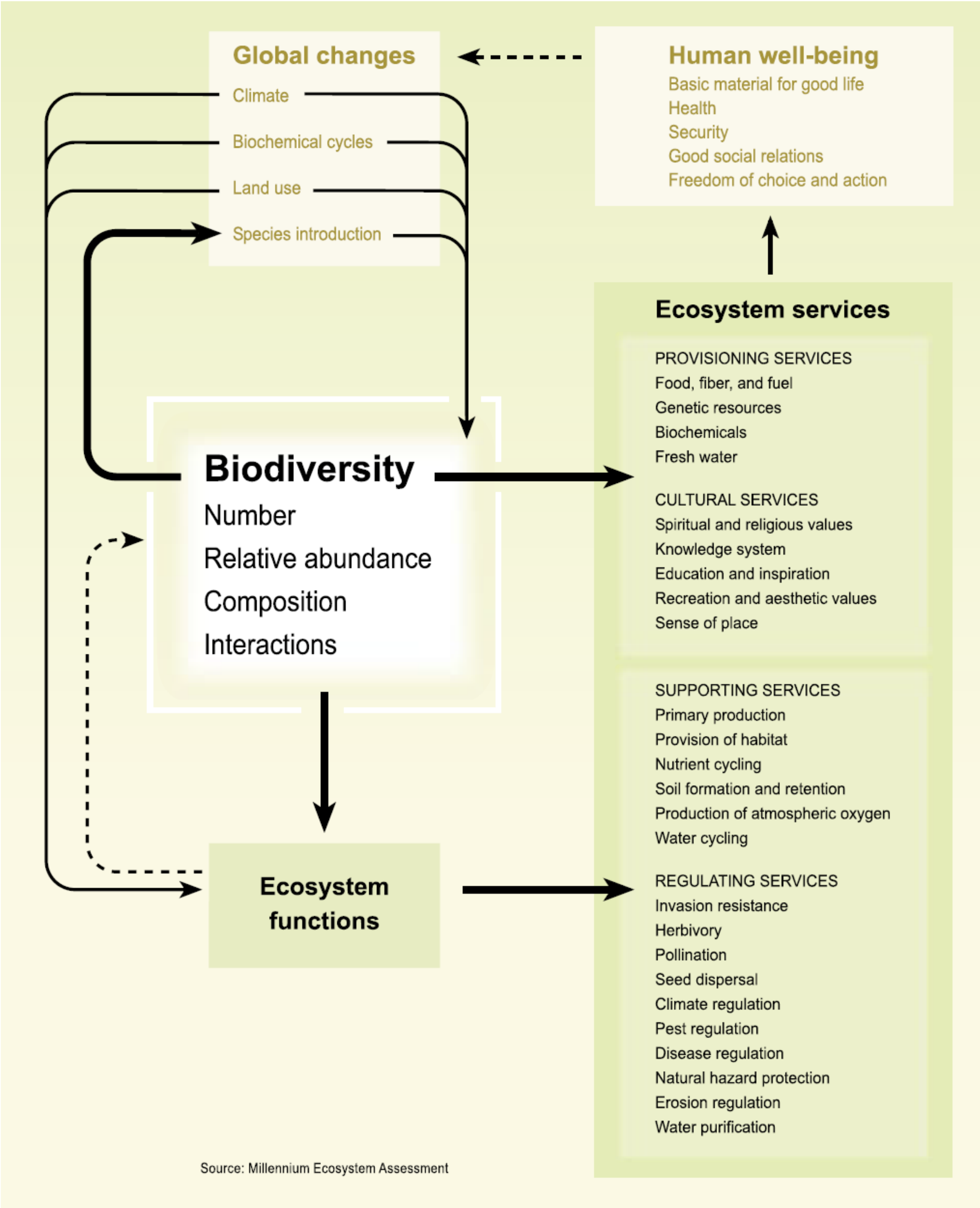

Figure 2: Biodiversity, ecosystem functioning and ecosystem services (source: MA, 2005b)

Methods

In the early stages of this project, as well as determining which ecosystem services were most relevant to the aims of the forestry component of the ICF, a methodology for the review was agreed to by the project partners. Systematic and repeatable search methods were adopted, including *a priori* criteria for inclusion of research in the review in order to ensure the review covered a comprehensive and unbiased cross-section of the literature. Critical appraisal of the evidence found was also undertaken to ensure conclusions were based on a thorough evaluation of the available information. However, a full systematic review, in the strict sense of the term, was not undertaken as it would have required narrowing focus of the review to a greater extent than was required to inform recommendations for the ICF. The specific methods used are described in detail in Annexes 1 and 2.

Through assessing the 16,000 papers found during the initial systematic literature search, about 1,200 papers were found which were relevant to the review (according to specific inclusion criteria, see methodology annex for details). These 1,200 papers were then subjected to detailed review, and the total number for the final review was further refined. In addition, this report has undergone an external expert review process, and evidence found in the review has been complemented by a number of key sources recommended by the expert reviewers. In order to summarise the evidence collected as part of this review, estimates of overall confidence of the linkage between biodiversity and the ecosystem services mentioned were made, based on the UK NEA confidence descriptions (UK NEA, 2011). The four different levels of confidence are:

1. **Well established**: High agreement based on significant evidence.
2. **Established but incomplete evidence**: High agreement based on limited evidence.
3. **Competing explanations**: Low agreement, albeit with significant evidence.
4. **Speculative:** Low agreement based on limited evidence.

These assessments drew on varying types and amounts of research that were available on the different relationships examined in this review. Some relationships are examined by numerous studies, while others are lacking in research. Additionally, some studies focused more on the theoretical relationships while others included more observational and experimental research, from single sites up to global assessments and reviews. For the purposes of this review, as the nature of the different studies varied, each reviewer assessed the strength of evidence based on a critical assessment of the paper jointly with the volume of research, rather than simply the number of papers supporting the relationship. It is also important to note that exploration of these relationships is an active field of research, with new papers released frequently. This review has assessed the evidence captured through its methodology and available up until December 2013. Additional papers may be found if more recent searches are conducted or wider search terms considered.

This review report is structured as follows:

- **Part 1** presents the detailed findings of the review based on three categories of ecosystem services: carbon stocks and their resilience; other regulating services (including primary productivity, soil erosion control, soil fertility and nutrients, pollination, seed dispersal, fisheries enhancement, disease prevention, biological control, water purification and regulation, protection from natural hazards, climate regulation and pollution control) and provisioning services (timber and non-timber forest products, NTFPs).
- **Part 2** provides policy guidance through a discussion of lessons from these findings for the forestry component of the ICF, including recommendations related to specific interventions in tropical forests that can result in synergies and trade-offs between outcomes for biodiversity, carbon storage and other ecosystem services.
- **The annexes** cover the key terms used and methods employed, and provide a table showing the trade-offs and synergies between different policy objectives related to biodiversity, carbon storage and other ecosystem services associated with a range of forestry interventions.

Part 1. Detailed findings

1.1 Carbon sequestration and storage, and the resilience of carbon stocks

Important climate-related functions of forest ecosystems are carbon sequestration and carbon storage, which create carbon stocks. The persistence and resilience of these carbon stocks as well as the continued ability of forests to absorb carbon dioxide from the atmosphere are significant factors in the role that forests can play in climate change mitigation (Díaz et al., 2009), particularly in a world characterised by rapid change. This section is built on a critical review of five existing reviews and syntheses on biodiversity and, carbon stocks and their resilience (Brodie et al., 2012; Midgley et al., 2010; Miles et al., 2010a; Parotta et al., 2012; Thompson et al., 2012), as well as additional related literature found through supplementary searches. As such, this section has not applied the same search and appraisal methodology as other sections of the review; however, the findings are presented in a similar way, using the same levels of confidence as applied throughout the review.

1.1.1 Carbon sequestration and storage

Globally there is a generally positive relationship between biodiversity and carbon stocks (Midgley et al., 2010): tropical moist forests, unaffected by direct anthropogenic disturbances like logging and fire, are rich in both. Within tropical forests there is less correlation between spatial patterns of carbon stocks and biodiversity in undisturbed areas and the patterns are complex (Talbot, 2010). At the macro-level, there is considerable variation from one tropical forest region to another in the number of species supported per unit area, but there is as of yet no compelling evidence that the most diverse tropical forests are also the most carbon-rich. In Amazonia there is little correlation between areas of highest species richness and areas of highest above ground biomass (Talbot, 2010). A great deal of uncertainty still surrounds biomass distributions and their causes, and different research groups and different approaches (including remote-sensing and ground-based measurements) have found different results. Overall, few studies yet exist that address whether the variation in biodiversity coincides empirically with large variation in biomass and soil carbon stocks.

Whether and to what degree biodiversity influences carbon stocks in tropical forests is still uncertain, although experimental work in other ecosystems has shown that biodiversity often promotes stability and primary productivity, and therefore carbon stocks (Miles et al., 2010a).

There is clear evidence to suggest a theoretical link between biodiversity and ecosystem functioning[3] (Loreau and Hector, 2001) (see also section 1.2.2 on productivity). Ecosystem functioning is important for maintaining levels of carbon sequestration (Díaz et al., 2009), although it is often dependent on mediating variables such as resource availability (Laliberté et al., 2013). The clearest evidence for species richness impacting ecosystem function comes from grassland ecosystems, through both experimental manipulations and observations (Thompson et al., 2012). There are only a few relevant observations for forest, but ecological theory suggests that the pattern should hold true for forests as well. Many of the grassland studies were carried out as tests of key ecological hypotheses, and as such implied that their conclusions might be expanded to cover other, more

[3] Ecosystem functioning is defined as “the flow of energy and materials through the arrangement of biotic and abiotic components of an ecosystem. It includes many ecosystem processes, such as primary production, trophic transfer from plants to animals, nutrient cycling, water dynamics and heat transfer” (Díaz and Cabido, 2001).

complex, environments. However, the relationship is probably more complex in hyper diverse systems such as tropical forest (Srivastava and Vellend, 2005). As tropical forests are more complex, have species richness orders of magnitude higher, and have less well understood dynamics, there is a high degree of uncertainty as to whether patterns and relationships found in experimental communities will be reflected in tropical forests. It is similarly unclear whether biodiversity effects levels off after a certain number of species are present.

There is *established but incomplete evidence* supporting the link between biodiversity and forest carbon sequestration. The relationship between biodiversity and the ability of an ecosystem to store carbon has been investigated by a number of studies. For example, Bunker et al. (2005) investigated a well-studied 50-hectare tropical forest plot in Panama. Through modelling 18 possible extinction scenarios (i.e. differentially removing species with different categories of traits: endemics, widespread and randomly occurring) within the plot they found above ground carbon stocks varied by more than 600% depending on the residual species composition. This suggests that the future carbon storage in tropical forests will be influenced strongly by future species composition, and therefore composition is a component to be considered carefully.

Healy et al. (2008) conducted an experimental manipulation of tree biodiversity in a number of experimental tropical tree plots, and found that a positive relationship existed between increased levels of biodiversity (in terms of species richness) and tree growth, but found no relationship between biodiversity and tree mortality. Potvin and Gotelli (2008) found that compared to monoculture experimental plots, mixed-species plots yielded, on average, 30-58% higher total tree basal area, indicating higher rates of tree growth. Through simulation models they demonstrated that the increased yield of mixed-species plots was due mostly to individual tree growth being enhanced rather than the addition of further individuals, resulting in an increased biomass. In comparing the effect of species richness versus 'environment' and 'space', Ruiz-Jaen and Potvin (2010), found that tree diversity predicted tree carbon storage in tropical forests with very high species richness. They found that key components of biodiversity, i.e. species richness and dominance of particular species, were complementary mechanisms for maintaining carbon stocks. It is also important to note that some systems with high productivity (e.g. secondary forest, grassland) have lower *net* carbon sequestration (storing less carbon in biomass and soil), than systems with lower productivity (e.g. boreal forests or old-growth natural rainforest) (Díaz et al., 2009).

A recent study by Conti and Díaz (2013) examined the role of functional biodiversity in facilitating carbon sequestration in semi-arid forests, looking at three major measures of functional biodiversity: the most abundant functional trait values[4]; the variety of functional trait values; and the abundance of particular species. They found that all three major components of plant functional diversity contributed to explaining the observed distribution of carbon stocks. Conti and Díaz (2013) conclude that the relative abundance of species with tall, and to a lesser extent dense, stems with a narrow range of variation around these values were the most important factors for predicting carbon sequestration. However they found no evidence of niche complementarity for promoting carbon storage. Kirby and Potvin (2007) examined evidence for a functional relationship between species diversity and carbon storage in managed tropical moist forest, agroforests and pasture in Panama.

[4] Referring to plant functional traits, Roscher et al. (2012) describe these as "morphological, physiological and phenological features measurable at the individual level which modulate plant performance and individual fitness via their effects on growth, survival and reproductive output (citing Violle et al., 2007), highlighting that plant traits are important determinants of how individual plant species contribute to processes at the community-level.

Although no direct relationship between diversity and carbon storage was found, the relative contributions of species to carbon storage per hectare in forests and agroforests were highly skewed and often were not proportional to species' relative abundances. Kirby and Potvin (2007) concluded that protecting forests from conversion to pasture would have the greatest positive impact on carbon stocks, even though the forests are managed by community members for timber and NTFPs.

1.1.2 The resilience of carbon stocks

Two aspects of carbon storage, ecosystem functioning (e.g. carbon sequestration) and forest resilience, are both equally important to net carbon storage. A key question when thinking about how biodiversity does or does not confer resilience is which stressors it is important to be resilient to (Carpenter, 2001). In this case, we are interested in the resilience of carbon stocks to disturbances related to climate change, such as increased temperatures, atmospheric carbon dioxide (CO_2) and precipitation, as well as increased rainfall seasonality (e.g. droughts), and extreme events like storms and fires (Laurance et al., 2009). It is also important to consider the interactions between climate change and other stressors, such as land use change, which are likely to be at least as important as abiotic changes (Brodie et al., 2012).

It is *well established* and there is a good theoretical grounding[5] that biodiversity confers resilience to some types of ecosystems, including in experimental plant communities (Tilman et al., 2006; van Ruijven and Berendse, 2010), urban socio-ecological systems (Jansson and Polasky, 2010), and coral reefs (Hughes et al., 2007), and is important for maintaining higher levels of ecosystem service provision (Gamfeldt et al., 2013). Targeted research on the role of biodiversity in forest carbon stock resilience would help to identify which forests are most likely to retain their stocks in future (in the absence of other pressures). Miles et al. (2010a) reviewed the evidence that biodiversity, intactness and naturalness affects forest carbon stock resilience. They found that all papers (including observations in forest ecosystems and experiments in grasslands and microcosms) showed that biodiversity has positive effects on resilience.

There is evidence to suggest that biodiversity confers *resilience* (in terms of recovery and stability of carbon stocks) to ecosystems more than *resistance* (that is whether it is affected by an event at all). For example, van Ruijven and Berendse (2010) tested the response of experimental plant communities to a natural drought to differentiate between the effects of plant diversity and biomass on resistance, recovery and resilience. They found that recovery of biomass after drought was related to species richness more than pre-drought biomass, but species richness did not affect resistance to drought. In a review of evidence from forest ecosystems, Thompson et al. (2012) concluded that any relationship between species richness and resistance is likely to be highly specific to the type and context of the ecosystem in question.Greater biodiversity is reported to increase forest resilience to changing environmental conditions. Bunker (2005) concluded from an experiment in tropical forests that different components of biodiversity, including identity, relative abundance, number and spatial arrangement of species in principle probably have an impact on stability and predictability of carbon stocks. The way in which forests respond to increasing rainfall seasonality is also of critical importance. Droughts are likely to cause higher rates of mortality, which may affect species composition. Drier forests are likely to increase fire frequencies (Bunker, 2005). Bond et al. (2005) showed that in a world without fire, many grasslands and savannahs would revert

[5] For example, see: Elmqvist et al., 2003; Folke et al., 2004.

to forest. Thus, in a world of increasing fire frequencies, it is likely that many forests could transition to grasslands and this will have dramatic effects on carbon stocks at various scales.

There is evidence that functional traits (e.g. ecologically-important characteristics) are more important for ecosystem resilience than species richness *per se* (Thompson et al., 2012; Midgely et al., 2010). Forests with greater diversity are likely to contain a wider diversity of functional traits than those with lower diversity. As mentioned, the presence of particular species in a community is likely to confer resilience because of a particular response type, and such species are more likely to be present with greater species richness (the 'sampling effect', where species richness increases the chance that a highly productive species will be present, and subsequently comes to dominate (Cardinale et al., 2007)). In van Ruijen and Berendse's study (2010), it was the presence of a particular species that conferred resilience to the system, conferring greater recovery in plots of higher species richness.

The type of disturbance encountered will also be important in determining which aspect of biodiversity is important for conferring resilience. In species-specific disturbances (such as increased bushmeat hunting during longer dry seasons), the insurance hypothesis may be important. This says that biodiversity confers resilience to systems through the mechanism of functional redundancy. If a dominant species important for ecosystem functioning declines due to disturbance, the loss is mitigated by others fulfilling the same role. Miles et al.'s 2010 survey found observational evidence for this effect in forest ecosystems (Elmqvist et al., 2001), and experimental evidence in grasslands (Tilman et al., 2006) and microcosms (Naeem and Li, 1997)[6]. Bunker et al. (2005) found that among their models of extinction scenarios, biological insurance[7] varied by more than 400%, depending on the remaining species composition. In more generalised disturbances, the response diversity of different species will likely be important, including their adaptive capacity (Walker et al., 2006).

Other aspects of biodiversity important for resilience are landscape level diversity, which can mitigate impacts of large disturbances (Gunderson and Holling, 2002), and genetic diversity, which provides a considerable contribution to ecosystem resilience (Gregorius, 1996; Reusch et al., 2005). Forest resilience emerges from diversity present at multiple scales, through genetic, species, and landscape heterogeneity (Thompson et al., 2012).

It is *well established* that the carbon stocks of intact forests are more resilient than those of degraded or fragmented forest. There is some evidence that degradation (or poor ecosystem condition) decreases resilience to external perturbations; for example, the recovery rate of rainforest landscapes in Borneo decreased following repeated cultivation (Lawrence et al., 2005). Recovery of secondary forest depends on the available species (including seed banks). In some forest ecosystems, the condition of the forest may deteriorate to the extent that recovery does not occur at all (new system state). However, though a general pattern can be found that more natural forests (associated with higher levels of biodiversity) confer greater levels of resilience (particularly recovery) to ecosystem stress and disturbance, the recovery time varies considerably within and among forest types (Thompson et al., 2012). Therefore preserving more natural forests is likely to

[7] Defined as the ability of an ecosystem to buffer itself against changes, as measured by the number of 'redundant' species present, the more species an ecosystem has the greater likelihood that for any given functional role, another species exists that undertakes the same role, which will respond differently to environmental perturbations (Bunker et al., 2005).

increase recovery rates and decrease variability across space and time for carbon storage. Plantations that include mixes of tropical species tend to produce higher biomass than monocultures (due to niche complementarity; see sections 1.1.1 and 1.2.2). Furthermore, plantations tend to have larger even-aged stands, which decreases resistance compared to natural forests, which tend to be more mixed in age (Miles et al., 2010a). More varied species composition in natural forests appears to increase regeneration compared to plantation forest.

In terms of intactness, there is clear experimental and observational evidence in tropical forests to suggest that large contiguous forest areas are more resilient than smaller patches. Laurance et al. (2000), for example, showed that the resistance of large trees in Amazonia reduced with decreasing patch size. Miles et al. (2010a) found six such papers providing evidence for this hypothesis and only one paper showing evidence against.

1.2 Other Regulating Services

Regulating services are “[t]he benefits that are obtained from the regulation of ecosystem processes”(MA, 2005a). This section examines evidence related to biodiversity and forest ecosystems and the following regulating ecosystem services: productivity; soil erosion control; soil fertility; pollination; seed dispersal; fisheries enhancement; disease prevention; biological control; water regulation and quality; protection from natural hazards; climate regulation (other than services related to carbon storage and sequestration, which are considered in section 1.1); and pollution control. In general, there is less literature that examines the relationship between biodiversity *per se* and regulating services. Potentially linked to this relative lack of research, there is stronger evidence for the role that natural, intact forests play in providing regulating services than for a role for biodiversity within those forests.

1.2.1 General findings

Forests provide a range of regulating ecosystem services that are important not only locally, but also globally. The literature base provides evidence for the existence of a diverse set of regulating services, from increased ecosystem productivity (Healy et al. 2008; Potvin and Gotelli, 2008) to livestock protection (O’Farrell et al., 2008), which directly benefit people at a local scale, through to nutrient cycling (Vityakon, 2001) and climate regulation (Bonan, 2008), which benefit people at a regional and global scales. The benefits that these regulating services bring both globally and locally are extremely important, but unfortunately are often not fully considered by decision-makers (Costanza et al., 1997). A number of studies estimated the global value of regulating ecosystem services, which can be several times the world’s total GDP (de Groot et al., 2012; Sutton and Costanza, 2002; Costanza et al., 1997). However, it is difficult for global economic assessments to fully capture the value of regulating services to communities at the local level. They play an important role in supporting livelihoods and ways of life (O’Farrell et al., 2008), as well as human wellbeing. For example, they maintain and increase crop yields, allowing people to grow sufficient food (Potvin and Gotelli, 2008; Healy et al., 2008) and they protect communities from storms, flooding and other natural hazards (Mugagga et al., 2012; Sathirithai and Barbier, 2001).

1.2.2 Productivity

Ecosystem productivity is defined as the rate at which the ecosystem generates biomass and is therefore closely related to carbon sequestration (see section 1.1). However, the productivity of an ecosystem is not just relevant to impacts on carbon stocks and global emissions. It has a number of important implications at the local level for the people who rely on that ecosystem. For example, a high level of productivity can mean that local people can harvest timber more regularly or obtain greater yields from crops. The available literature provides evidence of a number of different mechanisms through which biodiversity can influence the productivity of an ecosystem, and of the benefits this may have for local communities.

There is *established but incomplete evidence* for a link between biodiversity and primary productivity. A number of studies suggest that increased species richness and diversity can increase the primary productivity of a system (e.g. Healy et al., 2008; Potvin and Gotelli, 2008; and discussed in section 1.1 on carbon sequestration). Cardinale et al. (2007), for example, summarise the results of 44 experiments with species from temperate grasslands, tundra, estuaries, or temperate bryophyte assemblages, showing that mixtures of plant species produced on average 1.7 times more biomass than monocultures, and were more productive than the average monoculture in 79% of all experiments. While this clearly illustrates the benefits of greater species richness, it should be noted that it was only in 12% of experiments that plots with more than one species achieved greater biomass than their single most productive species.

A number of studies investigating the link between species richness and biomass explain the findings of Cardinale et al. (2007) as a 'sampling effect', where species richness increases the chance that a highly productive species will be included in plots which contain multiple species (Cardinale et al., 2007). However, Cardinale et al. (2007) also showed that although this effect contributed to increased biomass, its contribution is equalled or exceeded by 'complementarity effects', where biomass is augmented by biological processes that involve multiple species, allowing more efficient use of resources and therefore higher productivity. Importantly, both these effects increase as experiments run longer, giving highly productive species and biological processes more time to affect productivity.

Panayiotis et al. (2004) tested the hypothesis that biodiversity effects on biomass should increase with available biotope space (the physical space associated with a species' niche) due to increased possibilities for species to use the available habitat in complementary ways alongside each other. In their study, they grew plants along a gradient of increasing soil depth and volume, offering increased rooting space to species. Their results provide support for the role of increased biotope space in strengthening the relationship between biodiversity and above- and below ground biomass due to complementarity effects between species.

There is *established but incomplete evidence* supporting the link between biodiversity and the functioning of trophic groups and ecosystems. Links between aspects of biodiversity such as species richness and identity and the functioning of trophic groups and ecosystems are explored by only a few papers in the literature examined. However, Cardinale et al. (2006) present a meta-analysis of studies, which shows that species diversity affects the functioning of numerous trophic groups (such as producers, herbivores, detritivores and predators) in multiple types of ecosystem. The study also assesses the extent to which productivity of ecosystems depends on average species loss, rather than the specific identity of the species that are lost (i.e. species richness effects vs. sampling effects). They conclude that average species richness does indeed affect the productivity of trophic groups, but that the magnitude of such effects was ultimately determined by the identity of species that were lost. Using experimental plant assemblages, Flynn et al. (2008) showed that species richness increased the reliability (reduced variation) of overall biomass production, but had no influence on the variation in biomass production of individual species or functional groups.

There is *established but incomplete evidence* that different management regimes can influence the relationship between biodiversity and the productivity of forest ecosystems. For example, Carreño-Rocabado et al. (2012) investigated the effects on taxonomic and functional diversity of logging regimes of differing intensity in an eight-year field experiment in the La Chonta forest concession, Bolivia. Taxonomic diversity was unaffected throughout the different disturbance regimes. However, at higher logging intensities the functional composition of forest species shifted towards 'fast-growing' species potentially fuelling increased primary productivity in the short term. In the medium term, a decrease in primary productivity can be expected as 'slow-growing' species have longer life spans. The authors concluded that modest harvesting levels did not have strong effects on the forest tree community, suggesting that this management regime can contribute to conserving functional biodiversity while also providing timber.

1.2.3 Soil erosion control

The review examined a total of 16 papers related to biodiversity, forest ecosystems and soil erosion control services.

There is a *well established* link between intact forest cover and the reduction of soil erosion[8]. Soil provides a fundamental service to an ecosystem by providing a medium and resources for plant life to live and grow. When soil erosion is high, ecosystem degradation and even collapse is a real risk. For example, when examining the collapse of fisheries in Lakes Naivasha and Baringo in Kenya, Hickley et al. (2004) concluded that the main cause was the extreme increase in turbidity, resulting in the near extinction of submerged macrophytes and a lake bed virtually devoid of benthic fauna. This rapid increase in turbidity was mainly caused by soil erosion linked to low vegetation cover caused by deforestation and overgrazing, and exacerbated by high intensity, sporadic rainfall on steep slopes. In a review of Zhangjiajie National Forest Park, China, Zhao et al. (2009) showed that the total reduction in soil loss due to the existence of the forest ecosystem is in the region of 2.77 million tons per year. On the basis of their findings, the authors recommended that although most of the near mature, mature and over-mature forest could be rationally cut and utilised by local communities, the soil protection service is extremely valuable and thus extensive timber felling should be strictly prohibited. Watkins and Imbumi (2007) reported that forest cover provides a crucial service to indigenous people in Mount Kulal, Kenya, by preventing rapid runoff in the short intense rainy season, which can cause significant soil erosion and loss of vegetative cover, in turn increasing the susceptibility of the land to further erosion. Similarly, in a comparison of plots in the Ziwuling region of the Loess Plateau, China, Zheng (2006) showed that following destruction of secondary forest, soil erosion in the region increased markedly and erosion rates in the deforested lands reached 10,000 to 24,000 tons per km^2 per year, which was 797 to 1,682 times greater than prior to deforestation.

A number of studies also provide evidence of the link between forest restoration and a reduction in soil erosion and surface runoff. Zheng et al. (2008) compared four different managed restoration treatments and a control area to show that surface runoff decreased by 63–88% and soil erosion by 76–97%, depending on the type of treatment. Natural secondary forest and tea plantations were found to be the most effective at reducing soil erosion and runoff compared to the control. Of the ecological variables measured in the study, vegetation structure and plant life forms were found to be the main factors responsible for reducing surface runoff and the movement of sediments. Zheng et al. (2008) made specific recommendations on management techniques, including that, in the early stages of forest restoration, mechanical cultivation should loosen the soil around the base of a tree only, instead of over the entire ground surface.

The importance of vegetation, including forest ecosystems, in retaining soil is also increasingly recognised by local landowners and communities. For example, In Ethiopia, the planting of woodlots

[8] See: Kim et al., 2013; McClain and Cossio, 2003; Mugagga et al., 2012; Watkins and Imbumi, 2007; Zhao et al., 2009; Zheng, 2006.

were associated by local inhabitants with soil depth and moisture improvement, while runoff, flooding and gully width were perceived as decreasing (Jagger et al., 2005).

1.2.4 Soil fertility and nutrients

The review examined a total of 14 papers related to biodiversity, forest ecosystems and soil fertility and nutrients.

There is *established but incomplete evidence* of a link between forests and soil fertility. The maintenance or enhancement of soil fertility can positively influence productivity within an ecosystem, and a number of papers provide evidence for the role that forest cover (including bushlands, secondary forest, woodlots and mangroves) plays in this process (for example: Hussain and Badola, 2008; Nielsen, 2007; de Souza et al., 2012; Vityakon, 2001; Ndayambaje et al., 2013) . De Souza et al. (2012) compared remnant forest fragments, agroforests and coffee plantations and found that soil quality (measured using a number of indicators including total organic carbon, microbial carbon, soil respiration and nitrogen mineralisation) was better in forest fragments compared to agroforestry and sun coffee systems. They also found a trend towards improved soil quality in agroforests relative to sun coffee systems after 13 years. Similarly, Vityakon (2001) concluded that work conducted in Northeast Asia provides strong evidence that soil fertility increases in the presence of trees. Leaf litter, for example, acts as an important agent facilitating nutrient cycling in these systems. Trees also play important roles in nutrient capture as roots prevent the loss of these nutrients through runoff. Vityakon (2001) suggested that species richness is important on the basis that the leaf litter of different tree species plays different roles in improving soil fertility, depending on their "quality" or chemical compositions. Ostertag et al. (2008) also showed that leaf litter recovered quickly with restoration but that species composition appears to have little influence on litter decomposition rates or on bulk soil carbon formation, when considered as mixed species litter. As abandoned agricultural and pasture lands become reforested, new species assemblages emerge and although these species combinations may strongly influence aboveground patterns and trophic interactions, their influence on litter inputs and soil carbon cycling may be less important (Ostertag et al., 2008).

Joshi and Negi (2011), in assessing the regulating services provided by pine and oak forests in the Western Himalayas, showed that the local community perceived the forests as providing valuable ecosystem services that helped to increase soil fertility through the decomposition of leaves and humus formation. A similar interview study conducted by McClain and Cossio (2003) also found that one of two major benefits identified by the local community as obtained from maintaining riparian forest was the maintenance of soil fertility near the river, allowing for high yields.

A number of studies examine the roles played by particular species groups in contributing to soil fertility. Nielsen (2007), for example, showed that bushland fragments in Tanzania are important in maintaining a high diversity and abundance of dung beetles, whose activity is known to enhance soil nutrient cycling and increase the capacity of the soil to absorb and hold water. Similarly, a systematic review conducted by Folgarait (1998) showed how ants help to regulate soil fertility. Folgarait (1998) grouped the services provided by ants as follows: physical changes, such as the movement of organic matter, bioturbation and structures that act to increase soil fertility and the infiltration of water; chemical changes, such as increasing the organic matter in the immediate area, and colonies acting to neutralise overly acidic and alkali soils; and changes in nutrient and energy fluxes, such as speeding up the natural flow of nutrients by feeding leaf matter to fungi they cultivate.

There is *established but incomplete evidence* supporting the link between biodiversity and the reduction of the loss of soil nutrients. A number of papers examine the influence of species richness and vegetation characteristics on the loss of soil nutrients. Wang et al. (2007) used experimentally created test plots of semi-humid evergreen forests to test the relationship between plant species richness and soil erosion processes, showing that surface runoff, soil erosion and total phosphorus loss decreased with increasing plant species richness. A number of studies also show the benefits of vegetation presence, biomass and types (rather than for species richness or other aspects of biodiversity) for preventing soil erosion or the loss of nutrients. In a study of shade trees in coffee plantations, Tully et al. (2012) found that the rate at which nitrogen was lost from the soil declined linearly with increasing shade tree biomass (with the biomass of shade trees being determined by the farmers' management plan). With regard to nitrogen management, Tully et al. (2012) recommended that farmers can decrease the loss of nitrogen from their soils by encouraging shade tree growth (balanced with the effects of increased shade tree density on yields). Molina et al. (2012) concluded that establishing herbaceous and shrubby vegetation as an understorey within forest plantations allows the formation of vegetated buffer zones in gully beds. This in turn enhances sediment trapping and increases infiltration, protecting the valuable topsoil from erosion.

1.2.5 Pollination services

The review examined 12 papers related to biodiversity, forest ecosystems and pollination services.

There is a *well established link* between biodiversity, including forest biodiversity, and pollination services[9]. The pollination services provided by insects, birds, bats and mammals are crucially important for non-wind pollinated crops and other plants. Olschewski et al. (2006) found that the insect diversity, specifically the species richness of bees, in the forest fragments adjacent to a coffee plantation was significantly related to coffee fruit set, providing strong evidence of a link between biodiversity and regulating ecosystem services. In addition, the paper quantifies the value of this ecosystem service, estimating the economic impact on coffee sites with increasing distance from a 100-ha circular forest area. In Sulawesi, the average net revenues of the adjacent coffee area (192 ha) were reduced by 7%, from USD 85 to 79 per hectare, due to the increased distance to the remaining forest. Similarly, Munyuli (2012) found that for coffee plantations, the potential yield and bee contribution to fruit set were positively related to bee abundance, species richness and foraging rate, and thus to the amount of semi-natural habitats available in the surroundings. While the majority of the literature focuses on the linkage between bee species and pollination, a large number of other animals that can be linked to forests also act as pollinators.

A substantial portion of evidence regarding the role of biodiversity in supporting pollination comes from studies that examine the loss of pollination services following the degradation and loss of habitat, suggesting a link between intact forest habitats and pollination. For example, Brosi (2009) focused on the effects of forest fragmentation on euglossine bee communities, which are a critically important group of tropical forest-dependent pollinators and whose decline is of significant concern. Brosi found that the abundance of euglossine bees was positively related to forest fragment size,

[9] See: Jha and Dick, 2010; Munyuli, 2012; Olschewski et al., 2006; Peakall, 1988; Rostás and Tautz, 2011.

negatively related to shape, quantified by the edge to area ratio, and marginally related to fragment isolation. When looking at bee species richness, similar patterns were noted, but the trends were statistically weaker with species richness being significantly positively related to the quantity of forest edge, marginally negatively related to fragment area, and unrelated to fragment isolation.

Kennedy et al. (2013) found that the most important factors enhancing wild bee communities in agro-ecosystems were the amount of high-quality habitat surrounding farms in combination with organic management and local-scale field diversity. These findings suggest that as fields become increasingly simplified with large monocultures, the amount and diversity of habitats for wild bees in the surrounding landscape become even more important. On the other hand, if farms are locally diversified then the reliance on the surrounding landscape to maintain pollinators may be less pronounced. Taki et al. (2007) examined the impacts of forest loss on pollinator communities and found through regression analyses that the abundance and species richness of all collected bees were positively related to only the forest cover, and that the seed set of trout lily (*E. americanum)* positively correlates with forest cover. These results indicate that forest loss causes negative impacts on potential pollinator communities and seed sets of some woodland plants.

Forest fragmentation has also been found to significantly influence the flower visitation rates of Euglossine bees, with visitation rates declining with fragment size, even where the openings separating fragments and continuous forest tended to be narrow (as little as 100 m) (Powell and Powell, 1987). Aizen and Feinsinger (1994) found that fragmentation can have additional more subtle impacts on ecosystem service provision; as fragmentation increased in the Chaco Serrano, for example, the flower-visitor insect fauna increasingly became dominated by an exotic honey bee, with potentially significant consequences for pollination rates. In a subsequent study of the impacts of fragmentation on pollination rates and fruit setting, Aizen and Feinsinger (1994) found that overall significant or non-significant reduction in pollination (pollen tubes) occurred in 81% of species, and reduced fruit set and seed set occurred in 73% and 79% (seed set) of the species respectively.

Brosi et al. (2008) investigated how forest landscape characteristics affect bee diversity and abundance. While they did not find any relationship of either the diversity or abundance of bees with forest fragment size, shape, isolation and landscape context variables, they did find strong changes in bee community composition associated with such variables. In particular, tree-nesting meliponines, which are social stingless bees, were associated with larger fragments, smaller edge to area ratios and greater proportions of forest surrounding sample points, while introduced *Apis* showed the opposite patterns.

1.2.6 Seed dispersal

This review found *speculative* evidence for a link between biodiversity and dispersal of seeds. Although a range of different species and groups (including insects, birds and mammals) are known to be important for the dispersal of seeds, only one paper examining the link between seed dispersal services and biodiversity was identified through the review methodology. The presence of particular species can be vital for Seed dispersal of many forest plant species is dependent on particular animal species or groups. Lengyel et al., found that a wide variety of plant species and genera (2.5% of all plant genera) have evolved mutualistic relationships with ants, including specialised structures to ensure seed dispersal (2010). Loss of biodiversity in such groups may therefore affect plant community composition.

Other related evidence, beyond that found through this review methodology, supports the link between seed dispersal and aspects of biodiversity. Chazdon et al. (2003), Tabarelli and Peres (2002), and many other authors have demonstrated the importance of a range of animal groups, including large vertebrates, in dispersing tree seeds to regenerating forest. Alterations to disperser communities, for example through hunting, can have significant impacts on the eventual composition of vegetation. Cianciaruso et al. (2013), in experiments of simulated loss of pollinators and dispersers, found that the impact on phylogenetic and functional diversity in savanna woody plants depended on the animal group extinguished.

1.2.7 Fisheries enhancement

The review identified five papers related to biodiversity, forest ecosystems and fisheries enhancement, including the role of mangroves.

There is *established but incomplete evidence* supporting the link between forest ecosystems and productivity in fisheries. The ecosystem services provided by tropical forests are not limited in their impacts to forest sites, as is illustrated by the case of mangroves. Hussain and Badola (2010) compared the benefits that mangroves can provide to fisheries in terms of the value of catches. They showed that in offshore fisheries areas with mangroves, the total catch (123 kg per fishing hour), the income from the catch (USD 44 per hour) and the number of species caught (44) were higher than in areas without mangroves (18 kg per hour; USD 2.62 per hour; and 24 species). In Asia, Chong (2007) conducted a review of the link between Malaysian mangrove ecosystems and fisheries, concluding that mangroves are unique and irreplaceable ecosystems that sustain coastal productivity. The continued ecological functioning of mangrove ecosystems not only maintained shoreline stability, but also supported rich biodiversity and coastal fisheries, as vital feeding and nursery areas. A number of other studies provide evidence additional to that identified in the review. The Government of India (2009), Bann (1998) and Hussain and Badola (2008) all show that mangroves act as a nutrient stock for both estuarine and marine ecosystems supporting local and commercial yields, and that mangrove forests act as nurseries for many fish species all along the eastern coast of India. McNally et al. (2011) found that by conserving mangrove ecosystems through the gazetting of a protected area in coastal Tanzania, shrimping and fishing incomes increased because of the increased provision of habitat for these species.

1.2.8 Disease prevention

The review identified two papers related to biodiversity, forest ecosystems and disease prevention.

There is *established but incomplete evidence* supporting the link between biodiversity and non-human animal and plant disease prevention, and *speculative evidence* supporting the link between biodiversity and human disease prevention. Both observational data and modelling provide evidence that forests play a role in reducing disease presence and transmission. For example, Mendenhall et al. (2013) found that forests play a role in reducing the presence of avian malaria; the proportion and configuration of countryside forest elements (forest fragments, remnant and other trees) within a 400 m radius, amongst other variables, was significant in explaining malaria presence. Further, when examining different land uses, they found that deforestation increased the prevalence of avian malaria dramatically. Keesing et al. (2006) also explored mechanisms through which species richness could increase or decrease disease risk, and illustrate the potential applicability of these mechanisms for both vector-borne and non-vector-borne diseases, and for both specialist and generalist pathogens. They showed that a diversity of hosts decreased the risk of disease, especially when pathogen transmission was frequency-dependent, and when transmission was greater within a species than between species. Keesing et al. (2006) cite examples that include diseases affecting humans and suggest that biodiversity and its manipulation could play a significant role in managing and reducing disease.

1.2.9 Biological control

This review examined six papers related to biodiversity, forest ecosystems and biological control services.

There is a *well established* link between biodiversity and biological control[10]. This applies to the biological control services provided by forests as well as to the effects of aspects of biodiversity, such as the presence of particular species. A study conducted by Mody et al. (2011) examined the factors that explain variance in the effectiveness of hymenopteran parasitiods in controlling apple blossom weevil in orchards. Through careful experimentation they found that parasitism was significantly higher on trees close (up to 50 m) to forest than on trees at larger distance (e.g. 200 m) to the forest. A number of studies have also specifically explored the effectiveness of ants as biological control agents keeping pest populations at bay in order to encourage larger yields in coffee systems, cacao agroecosystems, and fruit and timber plantations in Old World and Australian tropics, and in production of sapodilla fruit/plum (Philpott and Armbrecht, 2006; van Mele, 2008; van Mele and Cuc, 2001). In all these cases, ants were identified as being a particularly important natural predator that deserves recognition for the ecosystem services they can provide. Jirinec et al. (2011) undertook an experiment to determine the variables responsible for explaining variation in the provision of biological control of pests by wild bird species in shade coffee plantations in Jamaica. Their results suggest that the ecological connectivity between coffee habitats and the adjacent forest is important in determining provision of this service, and provides evidence that the provision of pest reduction services could be at least partly dependent on a farm's proximity to forest patches.

A review conducted by Tscharntke et al. (2011) concludes that shade trees in agroforestry enhance functional biodiversity, carbon sequestration, soil fertility, drought resistance, and weed and biological pest control. In the case of cacao trees aged beyond 25–30 years in unshaded plantations, dwindling yields and increasing pressure from insect pests led farmers to abandon plantations (Schroth et al., 2000; Johns 1999 in Tscharntke et al., 2011). The abandonment of old, unshaded cacao in favour of planting young cacao in new, thinned forest sites can be followed by losses due to unmanageable pest and pathogen levels. Hence, shade is often viewed by farmers as an effective insurance against insect pests, which explains why earlier government initiatives in Bahia, Brazil, had little success when trying to convince farmers to cut their shade trees and to rely on a "technological package" of agrochemicals (Cassano et al., 2008, Johns, 1999, in Tscharntke et al., 2011).

[10] Meaning biological regulation of pests and pathogens, such as the presence of predator-species of pest species. See: Mody et al., 2011; Philpott and Armbrecht, 2006; van Mele, 2008; van Mele and Cuc, 2001.

1.2.10 Water regulation and quality

The review examined a total of 18 papers related to biodiversity, forest ecosystems and water regulation and quality services.

There is a *well established* link between forest ecosystems and water regulation and quality[11]. Numerous studies show the importance of the presence and intactness of forest ecosystems and different types of vegetation (rather than biodiversity *per se*) in regulating water runoff and erosion, and therefore playing a role in regulating flows and maintaining clean water supplies (see also sections 1.2.2 and 1.2.3 on soil erosion control and fertility). Molina et al. (2012) studied the causes of change in river flow variables in a degraded part of the Andes, finding that shifts in the hydrological regime were associated with human-induced changes in vegetation type and density, most likely to be related to the conversion of native forests to agricultural land. In an economic valuation study of the water storage function of the Zagros forests in Iran, Mashayekhi et al. (2010), used a replacement cost method to estimate the economic value of water retention by natural forests in the Bazoft river basin, based on the costs of water storage in the Karoon 4 Dam, at USD 43.37 per hectare per year. This dollar value represents the benefits from existing forest cover in mitigation of flood damage and reduction of surface runoff.

Watkins and Imbumi (2007) in discussions with the indigenous people in Mount Kulal, Kenya, found that they regarded the forest as crucial for holding water and delivering it to the villages on and around the mountain. Intact forests at all levels, from the mist and cloud forests at the summit, to the Acacia forests on the shoulders of the mountain, aid in retention and absorption of the often short and intense rains. In a similar study, Joshi and Negi (2011) show that local people perceive pine and oak forests in the Western Himalayas as helping to sustain the flow of water in the streams due to their sponge-like effect, as well as maintaining soil moisture.

A literature review on the regulating services provided by riparian vegetation conducted by Tabacchi et al. (2000) identified three main services: i) the control of runoff; ii) the impact of plant physiology on water uptake, storage and return to the atmosphere; and iii) water quality. The authors conducted a rigorous analysis of the literature available and concluded that although evidence does indeed exist to support i) and ii), many unresolved issues remain concerning the exact role of riparian vegetation in the provision of water quality regulating services. In particular, little is known about the coupling of microbial and vegetational functions in nutrient cycling and the dynamics of carbon release from coarse and fine plant debris.

The relationship between forests and water regulation and quality is also considered a potentially strong tool for poverty alleviation. Brown et al. (2011) examine the outcomes of a tree replanting scheme for a community in Ethiopia, noting that while measurements have not yet been undertaken, it is anticipated that the increased vegetation cover and leaf litter from the planted trees will help to protect the fragile lateritic soils, reduce water runoff and erosion, and increase infiltration and groundwater recharge, thereby improving farming and living conditions. These outcomes are already supported by anecdotal observations made by community members. Douglas et al. (2006) also note that interventions may be of particular interest in basins where loss of the most threatened tropical forest areas would give rise to significant biodiversity loss and to

[11] See: Cui et al., 2007; Douglas et al., 2007; Hickley et al., 2004; Jim and Chen, 2009; Magette et al., 1989; Mashayekhi et al., 2010; McClain and Cossio, 2003; O'Farrell et al., 2009; Wang et al., 2007; Watkins and Imbumi, 2007; Zheng et al., 2008.

potentially large hydrological impacts. In such cases it is conceivable that biodiversity conservation could benefit from efforts to maintain forests in order to minimise hydrological change.

1.2.11 Protection from natural hazards

The review examined a total of 18 papers related to biodiversity, forest ecosystems and soil erosion control services.

There is a *well established* link between forests and other ecosystems and protection from natural hazards[12]. The role of the presence of forests and other ecosystems in reducing the risks to communities from natural hazards, such as landslides and coastal storms, is important for human well-being in terms of safety and the maintenance of livelihoods. Mugagga et al. (2012) investigated land use changes and the influences that these can have on the risk of landslides, finding that deforestation and cultivation both alter the soil hydrological conditions on steep concave slopes, rendering them susceptible to saturation. This increased susceptibility may trigger debris flows during rainfall events. In a study which combined experimental field observations of vegetation and modelling of the effects of this vegetation on the vulnerability of the site to landslide, Kim et al. (2013) show that rainfall interception by vegetation did not significantly affect the amount of rainfall reaching the soil surface, but instead changed the temporal distribution of the rainfall intensity. Trees appeared to make a significant mechanical contribution to reducing shallow landslide development during a severe storm event in steep, forested watersheds.

Sathirithai and Barbier (2001), looking at mangroves in particular, argue that they can act as a natural buffer against cyclones and storms, protecting vulnerable embankments from tidal surges. In a similarly focused review, Gedan et al. (2010) found that the literature supports the argument that mangrove and salt marsh vegetation affords protection from erosion, storm surges and potentially small tsunami waves, but that this protection is strongly context-dependent. In an overview of biophysical models, field tests and natural experiments, the presence of wetlands was found to reduce wave heights, property damage and human deaths.

Other protective regulating services provided by forest ecosystems are important, and this is recognised by communities. For example, in a study examining the reasons why the indigenous people of Chivi District, Zimbabwe chose to plant and manage trees, Gerhardt and Nemarundwe (2006) found that the main reasons included the provision of shade and windbreaks. Joshi and Negi's (2011) interviews with communities living in oak and pine forests in the Western Himalayas, showed that the communities perceived the forest as providing a number of important regulating services including assisting in tempering droughts and floods, and protecting against landslides through the effectiveness of the extensive root systems in anchoring rocks. When examining the uses of trees remaining in paddy fields in southern Lao People's Democratic Republic (PDR), Natuhara et al. (2012) found that farmers use trees for a wide range of purposes, including protection for themselves and their livestock from the sun.

Some investigations focus more directly on the link between aspects of biodiversity and the provision of protection services. Genet et al. (2010), for example, studied the influence of plant diversity on slope stability during the early stages of succession and found that different mixtures of

[12] See: Cui et al., 2007; Gedan et al., 2011; Iftekhar and Takama, 2008; McClain and Cossio, 2003; Mugagga et al., 2012; Natahura et al., 2012; Sathirithai and Barbier, 2001; de Souza et al., 2012.

species along the slope had no influence on slope stability, but that differences in root tensile strength between species played a small role in slope stability, and that tree size and density were the most important factors affecting slope stability (excluding hydrological factors).

1.2.12 Climate regulation

The review identified four papers related to biodiversity, forest ecosystems and climate regulation services.

There is *established but incomplete evidence* for a link between intact forest ecosystems and regional and micro climatic regulation. The literature reviewed suggests that the effects of forest on the climate vary depending on forest type and location. At a regional scale, Cui et al. (2007) modelled the impacts of deforestation on the southeast Tibetan Plateau, and the influence over the local and remote climate. Their models predict that deforestation would cause decreased transpiration and increased summer precipitation in the deforested area, and a wetter and warmer climate on the Tibetan Plateau in summer. The consequence of this change in precipitation pattern would be to produce more runoff into the rivers originating from the Plateau, worsening flooding downstream. Their models also show that deforestation would affect the regional Asian climate (strong droughts are predicted at the middle and lower reaches of the Yellow River) and even the global climate, although the statistical significance is small.

Evidence examined in this review shows that forests play a significant role in modifying climate at a local level, also called microclimatic regulation. De Souza et al. (2012) found in a study comparing agroforestry, remnant forest and sun coffee systems that agroforestry systems can moderate high temperature extremes. In addition to the immediate benefits that coffee growers obtain in terms of increased survival of their crop, agro-forest services are also thought to provide some resistance to expected near-future temperature increases resulting from climate change.

In urban areas, the effect of trees and urban forests on the microclimate is becoming increasingly recognised. Jim and Chen (2009) undertook a review of the ecosystem services provided by urban forests and identified microclimatic regulation as one of these services. They found that urban forests produce benefits that are both multidimensional and complex, including modification of solar radiation, wind speed, air temperature, relative humidity and terrestrial re-radiation (Miller, 1997; McPherson et al., 1997; and Grimmond et al., 1994; in Jim and Chen, 2009). The authors suggest that urban forests could produce an ‘‘oasis effect”, whereby the continuous evapotranspiration of water acts to cool the surrounding environment, in addition to other effects rendering the local environment, specifically with regard to its bioclimatic conditions, more comfortable. By calculating the cost of replacing the heat absorbed through this process, Leng et al. (2004 cited in Jim and Chen, 2009) estimated the value of this ecosystem service for Beijing as RMB 934,579 per day (USD 112,915 in 2004).

There is substantial literature relevant to forests and climatic regulation that was not identified through the searches used in this review, but which may still be of importance to the ICF. For tropical forests, at a large scale, research findings agree that these forests mitigate the effects of global warming by maintaining high rates of evapotranspiration, which decreases the surface air temperature and increases precipitation compared with pastureland (Bonan, 2008). Spracklen et al. (2012) found that in much of the tropics air passing over extensive vegetation produced at least twice as much rain as air that had passed over land with little vegetation. Results of climate model simulations agree that large-scale conversion of Amazonian forest would be followed by a warmer and drier climate (Coe et al., 2013; Shukla et al., 1990; Snyder et al., 2004; West et al., 2011). At local to regional scale, the impacts of deforestation on the climate can vary. For the Brazilian state of Rondonia, Butt et al. (2011) investigated changes in the onset of the rainy season following deforestation, using daily rainfall data covering time periods of at least 25 years. They found that in deforested areas the onset of the rainy season was delayed by on average 11 days over the past three decades, while the onset date in areas that were not heavily deforested had not changed significantly. Another study, however, found that rainfall in August, at the peak of the dry season, was higher over deforested areas of south-western Brazil than over forested areas (Negri et al., 2004). In southern Australia, an experiment along the rabbit proof fence examined the role of land cover change on the formation of clouds. Observations and numerical model analysis showed that the formation and development of the west coast trough and cloud formation was affected by land cover change, leading to a rainfall decrease to the west of the rabbit fence, i.e. where rabbits were still present and vegetation had been degraded (Nair et al., 2011).

1.2.13 Pollution control

The review identified three papers related to biodiversity, forest ecosystems and pollution control services.

There is a *speculative link* between forests, and pollution control. Jim and Chen (2009) in their review of the ecosystem services provided by the presence of urban forests describe the role that these forests can play in reducing air bound pollution. They highlight work by Yang et al. (2005) that attempted to value this ecosystem service. Using local field data, they estimated that trees could capture from the atmosphere 1261 tons per year of total air pollutants, including 772 tons of particulate matter up to 10 micrometers in size (PM_{10}), 256.4 tons of ozone, 132.3 tons of nitrogen dioxide and 101 tons of sulphur dioxide. Furthermore, the air pollutant avoidance due to reduction in cooling energy consumption (where the evapotranspiration effect of the trees would be substituted for air-conditioning using fossil-fuel derived energy) was estimated at 20,054 tons per year, with CO_2 representing the largest share. Forests may also be important in regulating air quality outside of cities; Joshi and Negi's interview study (2011) shows that local people in the Western Himalayas perceive forests as helping to purify the air, e.g. by capturing dust.

1.3 Provisioning services

1.3.1 Timber

The review examined a total of 34 papers related to biodiversity, forest ecosystems and the provision of timber.

Timber is a source of income for communities living in or near tropical forests, although there are *competing explanations* regarding the level of its importance. Apart from direct local uses, such as construction (Grundy et al., 1993; Vermeulen et al., 1996), timber is harvested for domestic and international markets. Godoy (1992) noted that due to the perceived high value of timber trees, tropical forests have typically been valued based on standing timber biomass, which overlooks the value of forest in terms of other ecosystem services. Income from timber can be particularly important as a safety net during periods of stress. A study by Njana et al. (2013) in villages adjacent to protected miombo[13] woodland in Tanzania found that a variety of livelihood strategies, including lumbering, were undertaken periodically to cope with food insecurity.

In contrast, in a meta-analysis of forest income generation by the rural poor population in 17 countries, Vedeld et al. (2007) found timber to account for a “surprisingly low” percentage of total forest income, and explained this as being potentially due under-reporting of illegal extraction. Further, timber trees may have importance in the provision of non-timber forest products (NTFPs, see section 1.3.2), including resin, oil, latex and seeds, causing a potential conflict between the competing uses (Guariguata et al., 2010; Herrero-Jáuregui et al., 2008). Several timber tree species in Central Africa and Brazil were reported to have competing NTFP and timber uses, sometimes leading to conflict between timber companies and local populations (Guariguata et al., 2010). Sal (*Shorea robusta*) is an example of a tree species which has economic value as timber, but also produces fodder, feed, resin, gum and other products (Webb and Sah, 2003; Gautam, 2005). In the case of Sal, the non-timber uses were considered to be of particular importance to local communities, with the implication that “timber-only forestry” could compromise local livelihoods (Gautam, 2005).

It is *well established* that pristine forests are important sources of many tropical timber species[14], although some species are successfully produced in biodiversity-poor plantation monocultures. Unlike fuelwood and many other NTFPs, which are often collected from secondary forests and fallow, timber is typically sourced from native, primary forests. Grundy et al. (1993) found that in Zimbabwe, local people used mainly riverside areas and miombo woodlands as sources of construction wood, whereas newly cleared land with remnant trees was seen to have very little relevance for construction purposes. In a study of paddy field remnant trees in southern Lao PDR by Natuhara et al. (2012), timber was found to be mainly extracted from forests, whereas farmland trees were used for other purposes. Historically, within the Brazilian Amazon, lumber mills were established near undisturbed forests which were sources of the economically valuable mahogany (*Swietenia macrophylla*) (Browder, 1989). Following the depletion of mahogany, new settlements were established on untapped forest areas (Browder, 1989).

A wide variety of different forest tree species are used as timber, and tropical forests with high species diversity often host a large number of timber tree species. Typically, timber from areas with high numbers of species with timber utility are used for a greater variety of purposes (Njana et al. 2013a; Vermeulen et al. 1996) For example, Herrero-Jáuregui et al. (2008) identified a total of 200 timber species out of a total number of 1,257 tree species within one state (Pará) in the Brazilian Amazon. In forests adjacent to a Tanzanian miombo woodland, a total of 42 tree species were used for poles, and 18 species were used for timber (Njana et al., 2013). In a rural area in Zimbabwe, Vermeulen et al. (1996) found that of 81 species occurring in the study area, the local people to use 44 species for construction, out of which 14 species were particularly favoured.

[13] Referring to a region of tropical grasslands, savannas and shrublands in central and southern Africa, as well as the "miombo" trees (*Brachustegia* spp.) that dominate the area (WWF, 2014).
[14] See: Browder, 1989; Grundy et al., 1993; Natuhara et al., 2012; Naughton-Treves et al., 2007; Njana et al., 2013.

However, areas with high levels of species richness do not necessarily provide the greatest possible production of timber, especially in areas where non-native species are grown in monocultures (Herbohn et al., 2013; Chopra and Kumar 2004; Tabuti et al., 2009). Comparing timber extraction within forests of differing biodiversity (encompassing a number of metrics) in India, Chopra and Kumar (2004) showed that timber extraction may be higher in forests with lower biodiversity and vice versa. They suggested that a trade-off exists between timber extraction and existence of high-biodiversity forests. In a survey of smallholder and community woodlots in the Philippines, Herbohn et al. (2013) found that exotic species comprised over 30% of trees in mixed species plantations. The primary motivation for planting exotic species was reported to be their faster growth compared to native species (Herbohn et al., 2013). In a survey of woody species used by local communities in eastern Uganda, Tabuti et al. (2009) found that 15 out of the 26 woody species most valued for timber and other uses were indigenous, while the majority of farmers preferred non-indigenous tree species for planting.

There is *speculative* evidence that income from timber felling from protected forests is important to local livelihoods. Harvest from protected forests can be limited to subsistence purposes and/or NTFPs (Gram et al., 2001). However, due to the illegal nature of harvesting timber from protected forests, its importance for local communities is difficult to quantify (Fousseni et al., 2012).

Timber extraction often changes the species composition of tropical forests and reduces the availability of timber over the long term. High-value timber species, such as mahogany (*Swietenia macrophylla*) have been intensively logged in natural tropical forests, leading to local declines or extinctions (Gram et al., 2001; Browder, 1989). Currently, vast forest areas in Amazonia are depleted of the most economically valuable timber species (Gram et al., 2001b). Forests where valuable timber species have been exhausted are then seen to have less economic value and are generally more likely to be converted to farmland. The impacts on biodiversity caused by timber harvesting may also reduce the availability of NTFPs (Herrero-Jáuregui et al., 2008).

Reduced-impact logging (RIL) techniques were developed to reduce the environmental impact of timber felling, hauling and processing to forest biodiversity and carbon stocks. It has been suggested that reducing the impact of logging on forest biodiversity may improve the long-term productivity of the forest through improving regenerative capacity of the forest, and reducing vulnerability to fires (through reduced organic debris). However, Edwards et al. (2012), comparing RIL forests with conventionally logged and primary forests, found no evidence that RIL helped maintain biodiversity in the short term. Guariguata et al. (2008) studied the compatibility of timber and NTFP extraction in RIL forests of Guatemala and Bolivia, concluding that the negative impact of timber harvesting on NTFP extraction may be relatively small in low harvest intensities, and is also dependent on the spatio-temporal overlap between the two.

Better management of natural forests and planting timber trees outside forests have been suggested as means of improving the sustainable use of timber. Planting trees on farmland in agroforestry systems can increase the biodiversity of agricultural plantations, deliver other ecosystem services and potentially produce high-value timber at the same time. However there are challenges associated with this approach and outcomes depend on how such activities are implemented. In a study comparing planting schemes in the Amazon region, Hoch et al. (2012)

showed that the benefits may be constrained by lack of skills, limited investment and risks related to pests, diseases and natural disturbances. Tree planting was generally not considered viable due to its high cost (Hoch et al., 2012). Guariguata et al. (2010) suggested that better integration of the objectives of NTFP harvesting should be incorporated in timber management plans to better manage the conflict between the two uses of wood and other forest products. They also suggest that in situations where the economic and social value of NTFPs exceeds that of timber, the trees should be protected from logging (Guariguata et al., 2010).

1.3.2 Non-timber forest products (NTFPs)

Non-timber forest products (NTFPs) are all types of useful substances, materials and/or commodities from the forest that do not require harvesting trees. This section will examine evidence regarding the relationship between biodiversity and the provision of NTFPs generally and for the specific categories of food, fodder, medicinal products, and fuelwood.

It is *well established* that forests can be an important source of non-timber forest products (NTFPs) for local people in tropical countries. A number of studies confirm that NTFPs extracted from tropical forests are important for subsistence purposes or income generation[15]. NTFPs are considered to be a particularly important source of income for poor households (Ektvedt, 2011; Griffin, 2013; Kabubo-Mariara, 2013; McElwee, 2010; Goebel et al., 2000; Das, 2010; Vedeld et al., 2007; Tabuti, 2006) and for indigenous people (Harun et al., 2010). While many NTFPs have little market value, some species have substantial export markets: examples of such species include the Brazil nut (*Bertholletia excelsa*) and xate palm (*Chamaedorea* spp.) in South America (Guariguata et al., 2008).

Vedeld et al. (2007) conducted a meta-analysis of 51 case studies from 17 developing countries to estimate the importance of forest products for the income generation of rural communities. They found forest environmental income to constitute on average 22% of total household income. Wild foods, fuel, fodder and thatch grass were found to be the most important NTFPs, with wild food and fuelwood comprising on average 70% of forest income (Vedeld et al. 2007). However, a study by Ambrose-Oji (2003) in Cameroon challenged the view of the importance of NTFPs to local communities, showing that NTFPs formed a modest contribution (approximately 6% of income) of migrant communities living in the Cameroonian forest zone (based on preferences, not distance from the forest). They found that these communities chose to diversify their livelihoods away from those based on natural resource use, as this provided more secure incomes.

There have been attempts to estimate the total monetary value of forest products in a given area, however Gram et al. (2001) notes that the different methodologies used make it difficult to compare the results directly. In a study conducted in Amazonian floodplain forests, Gram et al. (2001) estimated the value of forest product extraction as approximately USD 13 per hectare per year. The generally low market value of NTFPs can limit the income opportunities of the poor from these products (Tesfaye et al., 2011).

[15] See: Brown et al., 2011; Das, 2010; Focho et al., 2009; Gautam, 2005; Goebel et al., 2000; Gram et al. 2001; Grundy et al., 2000; Harun et al., 2010; Herrero-Jáuregui et al., 2008; Narain et al., 2008; Ndangalasi et al., 2007; Ndayambaje et al., 2013; Njana et al., 2013; Tabuti et al., 2009; Tabuti, 2006; Tag et al., 2008; Tesfaye et al., 2011; Vedeld et al., 2007 .

Forests with high species richness generally provide a wider range of NTFPs. Based on their findings in communities adjacent to a Tanzanian forest reserve, Njana et al. (2013) suggested that the well-being of local communities was dependent on the diversity of tree and shrub species with different functions: providing fuelwood, construction materials, wild food, medicines and other important products. Brown et al. (2011) suggest that high functional redundancy (several species can be used for the same purpose) is an important factor defining the value of a forest as a source of NTFPs; in a forest with high functional redundancy, changes in species richness do not immediately lead to the loss of use value.

There are *competing explanations* on whether more pristine forests are better sources of NTFPs. Several studies show that protected forests are important sources of NTFPs for local communities in various parts of the tropics (Thapa and Chapman, 2010; Kimaro and Lulandala, 2013; Fousseni et al., 2012; McElwee, 2010; Ndangalasi et al., 2007). For example, in Nepal, communities living in areas adjacent to protected areas were considered to be dependent on legal and illegal resource extraction from the reserves (Thapa and Chapman, 2010). Kimaro and Lulandala (2013) found that the Ngumburuni forest reserve in Tanzania was a more important source of NTFPs than the land area outside the reserve, as supplies of NTFPs were higher. Ndangalasi et al. (2007) found that the extraction of NTFPs from two forest reserves in Tanzania and Uganda was important for livelihoods even when their exploitation was restricted by law. Fousseni et al. (2012) studied three protected areas in northern Togo, finding that although prohibited, the local population commonly used protected areas as sources of pasture, fuelwood, medicinal products, bushmeat and fish. In addition, the use of NTFPs, especially close to village borders, was found to have negative impacts on forest structure and diversity, and the use of ecosystem services (Ndangalasi et al., 2007; Thapa and Chapman, 2010).

The view of the importance of natural forests as providers of NTFPs to the rural poor was challenged by Ambrose-Oji (2003), whose study in Cameroon showed that secondary forests and fallows are in fact the major source of NTFPs rather than primary forests, which are more difficult to access. It was pointed out that there was a clear discrepancy between the areas that the local resource users considered most important, i.e. farmland and forest fallow, and the pristine forest areas that were the focus of conservation strategies (Ambrose-Oji, 2003). In southern Lao PDR, Natuhara et al. (2012) found that trees left on paddy fields supported many of the original uses of forest trees. A total of 71 species of trees growing on paddy fields were used by local people for fruit, fuelwood, medicine and shade. In Nepal, farmers' interest in planting trees on their farmland increased with increasing distance to natural forests (Griffin, 2013).

Food

The review examined a total of 46 papers related to biodiversity, forest ecosystems and food provision.

It is *well established* that foods derived from forest ecosystems play a vital role for poor and rural people in many tropical countries[16], playing primary roles in household wellbeing (Misra and Dash, 2000; Howell et al., 2000; Nkem et al., 2013) or subsidising households whose main income is from

[16] See: Golden, 2009; Howell et al., 2008; May et al., 1985; Mishra and Chaudhury, 2012; Misra and Dash, 2000; Mendelson et al., 2003; Montoya and Young, 2013; Mutenje et al., 2011; Nasi et al., 2011; Nkem et al., 2013; Nogueira and Nogueira-Filho, 2011; Okafor, 1980; Osemeobo, 2009 .

another activity such as agriculture, fishing, or timber production (Muafor et al., 2012; Mishra and Chaudhury, 2012; Nkem et al., 2013). This is particularly true for the rural poor (Mutenje et al., 2011), including those without access to land (May et al., 1985), indigenous peoples (Montoya and Young, 2013; Nasi et al., 2011; Misra and Dash, 2000; Mishra and Chaudhury, 2012; Nkem et al., 2013), and in one reported case in central Africa, the urban poor (Nasi et al., 2011). Bushmeat forms a key part of the diet of hundreds of millions or rural people (Golden, 2009). Besides using wild foods for their own consumption, communities are often dependent on other local natural resources, such as forest land for crop production and non-wood products for income, which indirectly affect household food supply (Nkem et al., 2013; Dembner, 1995; Newton et al., 2011; Mishra and Chaudhury, 2012). Mangrove forests also provide food resources through the provision of vital nursing grounds for marine species (Walters et al., 2008, see also section 1.2.7).

In addition to complementing staple foods throughout the year, **it is *well established* that forest foods can become critical for household coping strategies during times of stress[17].** Where the main livelihood is agriculture, forest food products may provide income, food and nutrients during lean months of the year (Misra and Dash, 2000; Nguyen, 1994), or for coping with drought (Gebauer et al., 2007). In an FAO study, in Mtara district, Tanzania, one particular forest species (*ming'oko* – a forest vine) played a crucial role in food security in lean months (Nguyen, 1994). Ibnouf (2009) shows that traditional rural communities in Sudan who used wild food resources maintained nutritious diets even during periods of drought, affirming the importance of such resources. Wild foods may also be important during periods of social upheaval or economic shocks (Howell et al., 2008). Mutenje et al. (2011) found that income from selling forest products offset economic shortfalls due to the impacts of HIV/Aids in South East Zimbabwe by roughly 48%.

It is *well established* that wild-gathered foods from forests and trees can be used to diversify the diet and livelihoods of rural communities[18]. Forest foods often complement staple foods from agriculture, adding flavour as well as vitamins and minerals important for nutrition (McGregor, 1995), particularly in impoverished communities and households. Indeed, by modelling the effects of wildlife removal from the diets of rural communities in Madagascar, Golden et al. (2011) found that children were three times more likely to develop anaemia when bushmeat and its associated micro-nutrients was removed, presumably because these families lacked access to alternatives. Wild-gathered foods can also form important supplementary sources of income, which is important for the diversification of people’s livelihoods, helping to reduce risk and food insecurity (Ibnouf, 2009). Howell et al. (2008) showed that the poorest households are also the most dependent on collecting foods and other natural resources, although the absolute financial returns were small. In South America, bushmeat hunting is not important for the total population or the economy, but remains so for the poorest communities (Nasi et al., 2011).

In addition to the studies found within the main search, Sunderland et al (2013) have highlighted the importance of wild food for vitamin A and calcium intake as well as iron.

[17] See: Dembner, 1995; Gebauer et al., 2007; Howell et al., 2008; Ibnouf, 2009; Jakobsen, 2006; Misra and Dash, 2000; Mutenje et al., 2011; Nguyen, 1994.

[18] See: Golden et al., 2011; Howell et al., 2008; Ibnouf, 2009; McGregor, 1995; Nasi et al, 2011; Nguyen, 1994.

It is *well established* that a wide variety of biological resources are apparently very important for maintaining food security[19] in rural populations[20]. A number of studies provide evidence that large numbers of different types of species are important as food sources, including plants, animals, insects and fungi (Golden, 2009; Gausset et al., 2005; Gavin, 2009; Gebauer et al., 2007; Nasi et al., 2011; Nkem et al., 2013). Misra and Dash (2000) found that although five species were key contributors to income generation of indigenous communities in Orissa, India, many more species were directly consumed in households, thus contributing to greater food security. Nasi et al. (2011) show that many types of mammal species are important constituents of bushmeat consumption in Amazonia and the Congo Basin, while Mishra and Chaudhury (2012) identified 150 species of wild and semi-wild plants important for indigenous people in the Koraput, India. Nkem et al. (2013) observed that Pygmys in Southern Cameroon were highly dependent on many different types of food, such as fruits, kernels, mushrooms, insects, honey, palm products and plants, as well as various animal taxa. Further, some papers conclude that biodiversity contributes to sustained ecosystem functioning in forest, which in turn generates the more direct ecosystem services of food (and other NTFPs) (Sircely and Naeem, 2012; and see section 1.2 on regulating services).

The availability of several species that can serve as a source for the same nutrients adds to food security if particular species decline. Indeed, biodiversity may be more important through its insurance function for food security, rather than for absolute amount or value of food. Misra and Dash (2000) found that indigenous peoples in Orissa, India, collected a wide variety of fruits and vegetables from forests that together represented a year round supply of food. Further, the diversity present within wild species may be important for food provision within agricultural settings. Some species are important wild relatives of crops or other commercial species, and offer possibilities for climate change adaptation or crop improvement; additionally, wild species exist that have presently unrealised agricultural potential (Mishra and Chaudhury, 2012).

Despite the range of species utilised, other studies contend that the principal component of biodiversity *directly* important for supporting household food security is the availability of particular species, rather than species richness *per se,* because of the specificity in regard to which species are used and which are not (Dembner, 1995; Gyan and Shackleton, 2005; Hanazaki et al., 2009; Ingramet al., 2012), and which are available (Nasi et al., 2011). Newton et al. (2011) showed that although forest foods were important, indigenous communities living in extractive reserves in Amazonia were more reliant on swidden agriculture or fishing as primary livelihood activities, because they were more temporally stable. However, the use of many different species may counteract this seasonality.

It is *well established* that intact forest ecosystems can provide greater availability of food products than secondary forests or degraded forest land[21], but that impacts on abundance vary between species (Okafor, 1980; Osemeobo, 2009). Gavin (2009) showed how mature forests provided more resources than secondary forests, except medicinal plants, while Ingram et al. (2012) found that of two species of liana whose leaves were eaten by humans, the preferred species was found in denser canopies. Osemeobo (2009) studied wild plants used daily in Nigeria. Of 27 species used daily for

[19] Here food security is defined as access to safe and nutritious food in adequate quantities to meet peoples' dietary needs for leading an active life, after Ibnouf, 2009.
[20] See: Gausset et al., 2005; Gavin, 2009; Gebauer et al., 2007; Golden, 2009; Okafor, 1980; Osemeobo, 2009; Misra and Dash, 2000; Nasi et al., 2011; Nkem et al., 2013; Sircely and Naeem, 2012.
[21] Gavin, 2009; Ingram et al., 2012; Jakobsen, 2006; Okafor, 1980; Osemeobo, 2009.

food, 65.3% came from natural forests. In this study, the number of species used for food was higher than any other category (including fuelwood, woodwork, dyes, medicine, etc), and the percentage of species derived from natural forests was also higher than any other category. Furthermore, only 5.3% of these species had been domesticated, compared to 24.3% of medicinal plants. In a village case study from North Central Vietnam, Jakobsen (2006) writes that 23 different products, including foods, are harvested from forests while nine are sourced from fallow areas; this is attributed to the larger area and greater diversity of vegetation of the forests. However, McGregor (1995) found that abundance of species varied with forest degradation: some species decreased while others favouring disturbed habitat increased. In addition, the vulnerability of particular species to harvesting varies, with some species remaining abundant or even prospering in heavily exploited secondary forests, while others need intact forests to remain viable (Nasi et al., 2011).

There is also evidence that the overharvesting of target species or degradation of habitats causes declining abundance or local extinction[22], potentially impacting the long term provision food products. Harvesting is likely to cause changes to the structure, function and composition of ecosystems, which may in turn affect other ecosystem service, such as regulating services (Nasi et al., 2011). Where dependency on wild foods or demand for them is high, interventions may be needed to prevent the decline of species that provide food and/or income (Ingram et al., 2012), and so ensure their sustainability. Morsello et al. (2012), for example, found that increased processing of bushmeat (to increase income from sales) led to increased harvesting effort, undermining the 'win-win' potential of using forest fauna to support livelihoods. Nevertheless, extraction of forest foods does have relatively little impact on forests and biodiversity compared to other activities. As expected, in a meta-analysis of drivers of deforestation and forest fragmentation in Asia by Mondal and Nagendra, harvesting of wild foods was not identifed as a key factor (2011).

The effect of forest degradation or species decline on the provision of food is also greatly dependent on how landscapes are managed by people, including local communities (Davidar et al., 2007; Menon et al., 2009; May et al., 1985), and other actors. The response to declining availability of wild-gathered and caught species governs how much species decline or how forest degradation will affect the provision of food related ecosystem services (Nasi et al., 2011; Misra and Dash, 2000). Many indigenous peoples modify or use forest habitats in different ways to suit their particular needs, including to support the provision of certain foods (Montoya and Young, 2013; Nath et al., 2005), or preferentially conserve some plant species as the landscape becomes increasingly human-modified (Misra and Dash, 2000). For the Bantu people in Cameroon, for example, secondary forest supplies nutrients that support their swidden agricultural practices (shifting cultivation), while primary forest is used increasingly for hunting (Nkem et al., 2013). People may also domesticate wild animals and plants to ensure continuing supply (Tapan et al., 2009; Nogueira and Nogueira-Filho, 2011).

Despite these findings, there are *competing explanations* about whether conservation improves food security through increased provision of wild foods. This is partly because the extent to which positive effects of conservation interventions for the species themselves confer benefits to ecosystem services depends on how the interventions affect the access local communities have to the ecosystems and potential services. For example, the benefits of protected areas – one type of

[22] Golden et al., 2012; Golden, 2011; Johnson and Grivetti, 2002; Okafor, 1980.

conservation strategy - can be checked by changes in access to these areas by resource-users (Golden, 2009). In contrast, McNally et al. (2011) found that by conserving mangrove ecosystems through the gazetting of a protected area in coastal Tanzania, shrimping and fishing incomes increased because of the increased provision of habitat for these species. In addition, there are often strong links between communities utilising forest foods and knowledge of which species are useful (Johnson and Grivetti, 2002; Ju et al., 2013; Mishra and Chaudhury, 2012; Muafor et al., 2012). It is important to consider local knowledge when designing interventions related to wild foods, to ensure that such knowledge is not lost, that the knowledge can contribute to the success of the intervention, and that community access to resources are taken into account.

Despite the contribution of wild foods to the livelihood strategies and food security of marginalised, vulnerable and rural peoples throughout the tropics, **there are also *competing explanations* regarding the role of food related ecosystem services in achieving the broader goal of alleviating and eradicating poverty** (Gubbi and MacMillan, 2008; Okafor, 1980; Nunes et al., 2012). This finding is partly attributable to barriers that prevent access by poorer households to higher-value forest products (Mitra and Mishra, 2011; Nkem et al., 2013;). For example, Nkem et al. (2013) found that it is the affluent members of the Bantu indigenous community of the high forest zone in Southern Cameroon who own guns for bushmeat hunting. Therefore, though high-value forest-derived foods may contribute to income generation in wealthy households, there may be constraints on poorer households accessing those same products, in order to make the transition from low to higher incomes. These barriers are likely to be greater in highly-stratified societies. However, the potential of poverty alleviation may also be limited by the increased strain on forest products following commercialisation (Muafor et al., 2012). On the other hand, there is some evidence that the marginal income derived from forest products may facilitate the acquisition of technologies that promote poverty alleviation, even though they may not be large in absolute terms. Muafor et al. (2012), for example, found that supplementary income from forest insects helped to pay for farming inputs .

Fodder

The review examined a total of 61 papers related to biodiversity, forest ecosystems and fodder provision, including papers drawn from an additional literature search conducted to supplement the main search.

It is *well established* that wild plants are crucial for feeding and maintaining livestock through provision of fodder[23]. In a wide variety of landscapes (Arjunan et al., 2005; Menon et al., 2009), fodder plants from native and primary forest ecosystems provide key sources of livestock feed for pastoralists' livestock (Stave et al., 2007) and small-scale agriculturalists with multiple livelihood strategies including livestock (Singh and Singh, 2011; Jakobsen, 2006). Fodder from natural ecosystems may also play a crucial role in feeding livestock during times of environmental stress (Singh and Singh, 2011; Jat et al., 2011). Trees within settlements and agricultural landscapes, as well as secondary forests and agroforestry systems, also provide key sources of fodder (Giraldo et al.,

[23] See: Ali et al., 2011; Badola et al., 2010; Griffin, 2013; Jakobsen, 2006; Jumbe and Angelsen, 2007; Kamanga et al., 2009; Kim et al., 2008; Musvoto and Campbell, 1995; Nagothu, 2001; Negi et al., 2013; Njana et al., 2013; Singh and Singh, 2011; Stræde et al., 2002; Ticktin et al., 2003; Vedeld et al., 2007.

2011; Nautiyal et al., 1998). There is a wide overlap between species used for fuelwood and fodder collection (Adnan, 2011; Davidar et al., 2008; Mondal and Nagendra, 2011).

It is *well established* that a wide range of species play an important role in supplying fodder for local people's livestock[24]. A variety of plant genera are used, including trees, shrubs, and understorey species and grasses (Giraldo et al., 2011; Singh et al., 2012). Stave et al. (2007) found that for Turkana pastoralists in northern Kenya, of 113 woody species, 79% could be used for feeding livestock (cattle, goats, camels, sheep and donkeys), higher than any other use category. In some cases, particular species are key contributors to meeting community needs (e.g. ardu *(Alianthus spp),* in Jat et al., 2011). However, there may be trade-offs between the provision of ecosystem services derived from forests and those from other ecosystem types (e.g. agro-ecosystems). Dalle et al. (2006), found that encroachment by woody species because of fire curtailment had a negative impact on grazing lands for pastoralists in the Borana lowlands, Ethiopia. In contrast, Stave et al. (2007), found that for Turkana pastoralists in northern Kenya, a high number of riverine forest species were used for fodder plants.

There is *established but incomplete evidence* that restricting access to forest resources will negatively affect local communities fodder requirements (Nagothu, 2001; Kamanga et al., 2009). Though use of forest resources including for provision of fodder may affect the sustainability of the resource (Arjunan et al., 2005; Davidar et al., 2007; Maikhuri et al., 2001; Nautiyal et al., 1998), the curtailment of use and access rights by the state may have a counterproductive effect on poverty alleviation and lead to conflicts, which could undermine conservation efforts**.** In India, for example, domestic forests have been proposed as a concept which incorporates the diverse ways in which forests have been transformed and managed by rural communities and reconciles conservation with livelihood needs (Menon et al., 2009), and this approach of reconciling conservation and livelihoods is popular across the world.

Medicinal products

The review examined 84 papers related to biodiversity, forest ecosystems and the provision of medicinal products.

It is *well established* that tropical forests - comprising native, secondary, and cultivated patches[25] - provide a major contribution to meeting the healthcare needs of indigenous and rural communities in developing countries, and for the development of conventional medicines[26] Traditional medicines are found in, or derived from, a wide variety ecosystems, including a diversity of forest habitats, such as mangroves (Walters et al., 2008), sacred groves (Ormsby and Bhagwat, 2010), cloud forests (Kappelle et al., 2000), primary rainforests (Herndon et al., 2009), forest fallows (Junsongduang et al., 2013), and savannas (Tabuti and Mugula, 2007). Resources additional to the papers found within the review search show medicinal plants are considered to contribute to the achievement of the Millennium Development Goals (MDG 8, Target 8.E – Access to essential

[24] See: Ali et al., 2011; Ishtiaq et al., 2013b; Kristensen and Lykke, 2003; Lykke et al., 2004; Njana et al., 2013; Stave et al., 2007.

[25] Comprising a mosaic of habitat patches including but not limited to mature primary forest, areas of varying degrees of natural disturbance and of human activity.

[26] See: Fleuret, 1980; Focho et al., 2010; Ghorband et al., 2012; Hamayun, 2007; Hanazaki et al., 2009; Haque et al., 2012; Hariyadi and Ticktin, 2012; Herndon et al., 2009; Ignacimuthu et al., 2006; Ishtiaq et al., 2013a; Jain et al., 2010; Junsongduang et al., 2013; Kappelle et al., 2000; Keirungi and Fabricius, 2005; Khan and Manzoor Rashid, 2006; Khan et al., 2009; Kitula, 2007; Mollik et al., 2010; Namsa et al., 2011;Ngari et al., 2010; de Oliveira et al., 2007; Ormsby and Bhagwat, 2010;Thomas et al., 2011; Veach et al., 2003; Vijayan et al., 2007; Walters et al., 2008.

medicines) for isolated and Indigenous communities (UN Technical Support Team, 2013). Genetic resources of medicinal plants also provide the basis for many modern medicines (Johnston and Colquhoun, 1996; Voeks, 2004), and comparative analysis on indigenous health systems has contributed to healthcare systems in western societies (Herndon et al., 2009). Furthermore, there is a significant trade in commercially-important medicinal plant species, most of which flows from developing to developed countries (Schippmann et al., 2002). In Africa, forest resources can play a key role in mitigating the impact of HIV/AIDS, being used particularly to boost the immune system and to treat secondary infections (Timko, 2013; Timko et al., 2008). The hill forests of the Western Usambara Mountains, Tanzania, provide 90% of medicinal plants used by local communities (Msuya and Kideghesho, 2009), while in rural communities in Kenya, it is estimated that 75-90% of rural communities rely on ethno-medicine (Kiringe, 2006). Medicinal plants are used for a wide variety of human ailments and diseases, such as malaria and intestinal diseases, and for treatment of livestock (Gaur et al., 2010; Gazzaneo et al., 2005; Giday, 2003; Yineger et al., 2007; Ishtiaq et al., 2013a). There is also substantial overlap between plants used for medicinal purposes and other provisioning uses, such as timber, fodder for animals, fibre and food (Sukumaran et al., 2008; Kamatou et al., 2011; Johnston and Colquhoun, 1996; Tabuti and Mugula, 2007; Ishtiaq et al., 2013b; Focho et al., 2010; Giday et al., 2009b; Gustad et al., 2004), as well as for providing various regulating functions.

An overlap between the practice of traditional medicine, and cultural and spiritual beliefs is discussed in a number of papers (Sukumaran et al., 2008; Khumbongmayum et al. 2005; Khan and Manzoor Rashid, 2006; Hariyadi and Ticktin, 2012; van Andel and Havinga, 2008; Tabuti et al., 2003a). Traditional healers and specialist practitioners are often involved in the provision of traditional healthcare using medicinal plants (Sorensen and Schjellerup, 1995; Fleuret, 1980; Giday 2003; Haque et al., 2012). The cultural and spiritual importance of forests can help protect medicinal plants provision, as in the case of sacred groves (Sukumaran et al., 2008). Men are more commonly reported as professional practitioners while women serve the healthcare requirements of their families (Sukumaran et al., 2008; Tabuti et al., 2003a; Giday et al., 2009b).

It is *well established* that many millions of people living in rural areas of developing countries are dependent on medicinal plants for their *main or primary source* of healthcare[27]. This is likely due to a lack of access to conventional medicine[28] (Iqbal et al., 2011; Khan et al., 2009; Fleuret, 1980; Tolossa et al., 2013; Gaur et al., 2010; Ghorband et al., 2012; Hariyadi and Ticktin, 2012), or the active choice to use medicinal plants over conventional medicines (De Wet et al., 2013; Focho et al., 2010). For many others, traditional medicines contribute to overall primary healthcare, along with conventional medicine (Namukobe et al., 2011; Veach et al., 2003; Tolossa et al., 2013; Tabuti et al., 2003a). Compared to conventional medicine, traditional medicines are accessible, cheap and socially acceptable (Ignacimuthu et al., 2006; Afroz et al., 2011; McElwee, 2010; Mulyoutami et al., 2009; Giday, 2003). This is particularly true in Africa (Ngari et al., 2010; Msuya and Kideghesho, 2009). Focho et al. (2010) found that conventional medicines were used only where no medicinal plant remedy was available. Further, the extent of the provision of medicinal products may reach beyond poor rural communities (Keirungi and Fabricius, 2005; McMullin et al., 2012; de la Torre et al., 2012;

[27] See: van Andel and Havinga, 2008; Giday, 2003; Hariyadi and Ticktin, 2012; Herndon et al., 2009; Ignacimuthu et al., 2006; Iqbal et al., 2011; Jain et al., 2010; Junsongduang et al., 2013; Khan et al., 2009; Khan and Manzoor Rashid, 2006; Keirungi and Fabricius, 2005; Nagendra and Gokhale, 2008; Namsa et al., 2011; Namukobe et al., 2011; Ndenecho, 2009; Thomas et al., 2011; Vijayan et al., 2007.

[28] Often this is stated by the authors rather than being explicitly examined or tested for in the study.

van Andel and Havinga, 2008). For example, Medeiros et al. (2013) found that medicinal plant use was not affected by urbanisation, demonstrating that this ecosystem service remains important to societies at higher levels of economic development than other types of ecosystem services that decline with increased urbanisation (such as fuel, timber and food).

It is *well established* that a large number of species appears to play a key role in delivering medicinal plant services to people[29]. A very wide variety of plants have medicinal properties, often greater than that used for food and timber (Junsongduang et al., 2013; Johnston and Colquhoun, 1996, Thomas et al., 2011; Voeks and bin Nyawa, 2006). India alone has more than 3,000 species of medicinal plants, and the total number of plant species of medicinal value worldwide has been estimated at 50,000 (Schippmann et al., 2002). Khumbongmayum et al. (2005) found that 96% of the 173 plant species in sacred groves of Manipur state, India, had medicinal uses. In ethnobotanical studies of traditional communities, high numbers (typically 50-100) of species are commonly recorded as useful (Ignacimuthu et al., 2006; Gaur et al., 2010; Kala et al., 2004; Gazzaneo et al., 2005). A wide variety of species are often used by communities, comprising a range of different plant forms and taxa (e.g. trees, shrubs, herbs) (Giday et al., 2009; Hanazaki et al., 2009; Vashist and Sharma, 2013; Howell et al., 2008), and other species may be used to 'catalyse' the effects of the primary ingredients (Haque et al., 2012). Fungi (Thomas et al., 2011) and occasionally animals are also used for medicinal uses (Hanazaki et al., 2009; Haque et al., 2012). A meta-analysis of ethnobotanical use patterns in Ecuador, de la Torre et al. (2012) found that the number of species used by a community was determined more by plant species richness in the surrounding ecosystem than socio-economic, environmental and geographical factors. Medeiros et al. (2013) found in a meta-analysis of Brazilian medicinal plant use that the type of plants used depends to a large extent on the ecosystem type. Native, woody, medicinal plants were used more in the Amazon than in the Atlantic forests and Pampas grasslands, where herbaceous or exotic species were most commonly used.

The literature predominantly shows the importance of particular species, rather than the number of species present, for medicinal purposes, because as with wild foods, there is a high degree of specificity with regard to which are perceived as useful, are preferred or are available (Tabuti and Mugula, 2007; Johnston and Colquhoun, 1996; Ishtiaq et al., 2013a; Kamatou et al., 2011). Globally, some plant families have higher proportions of medicinal species, such as the *Apocynaceae, Araliaceae, Apiaceae, Asclepiadaceae, Canellaceae, Guttiferae* and *Menispermacea* (Schippmann et al., 2002). Thomas et al. (2011) analysed how well represented different families were in known species inventories of two indigenous groups in the Bolivian Amazon. Though the most represented families were also the largest families, they found that some families were overrepresented, providing evidence that particular species (i.e. species identity) are more important than species richness. Ishtiaq et al. (2013b) showed that despite high plant diversity in Soona Valley, Pakistan, use value was concentrated in a much smaller group of species. Similarly, Kala et al. (2004) found that one species (*Vitex negundo)* was used to treat 48 ailments, while two endangered species (*Aconitum heterophyllum* and *Picrorhiza kurrooa*) were the most preferred of 148 different species for treating pains and fever, noted for their speed and efficacy.

[29] See: Fleuret, 1980; Gaur et al., 2010; Herndon et al., 2009; Ignacimuthu, et al., 2006; Ishtiaq et al., 2013b; Iqbal et al., 2011; Jain et al., 2010; Johnston and Colquhoun, 1996; Junsongduang et al., 2013; Kappelle et al., 2000; Khan and Manzoor Rashid, 2006; de Oliveira et al., 2007; Msuya and Kideghesho, 2009; Ngari et al., 2010; Sukumaran et al., 2008; Tabuti et al., 2003a; Vijayan et al., 2007.

There is *established but incomplete evidence* that higher species richness confers a greater degree of resilience to environmental change and stress, if more than one plant is used for the treatment of a condition (Júnior et al., 2011). Although only one study explicitly used the word redundancy (Júnior et al., 2011), the wide variety of studies showing that more than one species can be used for treating particular ailments suggest that the presence of multiple species can confer redundancy (e.g.: Afroz et al., 2011; Kala et al., 2004; Mollik et al., 2010; Namsa et al., 2012; Fleuret, 1980; Gazzaneo et al., 2005; Namukobe et al., 2011; Vijayan et al., 2007). Despite relative preferences for one species over another, the loss of one species from an area might be may be less consequential for the beneficiaries if other species can play the same role (Adnan, 2011; Nadembega et al., 2011). Fleuret (1980) found in a study of the Shambaa people's use of medicinal plants in Tanzania that up to 15 species could be used for the treatment of a single ailment. Sorensen and Schjellerup (1995) found that 24 species of plants were used to treat liver and kidney diseases, while Johnston and Colquhoun (1996) found 246 plant uses from 120 plant species in a study of Amerindian ethnobotany in Guyana, and that there is insurance in some use categories but vulnerability in others. Skin ulcers and sores were treated with any one of 17 different species, and malaria by 11 species. However, 18 of 46 different use categories (including particular health and other uses such as food) were provided by just a single species. In a study explicitly examining the role of redundancy of medicinal plants in treating various inflammations in Caatinga forests in Brazil, Júnior et al. (2011) found that "wounds", "cuts" and "uterus" were the most redundant categories, while five conditions were classed "non-redundant" in so much as they were treated by only one species. Redundancy also has a sustainability dimension; if many species are used for treating a condition and there are few overtly preferred species within that category, the harvesting pressure is likely to be shared amongst a greater number of species thus promoting sustainability (Júnior et al., 2011).

It is *well established* that secondary forests and disturbed habitats provide considerable quantities of medicinal plants[30]. As humans increasingly modify their environments, the proportion of medicinal products gathered from forests compared to those collected from anthropogenic or cultivated areas changes (Voeks, 2004; Keirungi and Fabricius, 2005). Further, different medicinal plants used for different purposes are found in different habitats, such as grass or shrublands (Kala et al., 2004; Yineger et al., 2007; Upadhyay et al., 2010). Importantly, as mature forests and woodlands become increasingly rare, medicinal plants associated with them become decreasingly represented in traditional medicine strategies (Keirungi and Fabricius, 2005). Although the use of different types of plants very much depends on availability (Medeiros et al., 2013), many medicinal plants are herbs that naturally will be found in patches of disturbance within forests and thus grow well in disturbed environments (Voeks, 2004, 1996; van Andel and Havinga, 2008). In a global review of 18 studies that compared the proportion of medicinal plants found in old-growth, secondary or disturbed habitats, Voeks (2004) found that old-growth tropical forests were important sources of wild foods, fibers and fuels, but were less important for medicinal plants. People were more likely to gather these from kitchen gardens and secondary forests.

In an explicit test of the hypothesis, Voeks (1996) found that traditional medicine practitioners in the Atlantic forests of Brazil had a strong preference for plants from disturbed habitats over primary

[30] See: Keirungi and Fabricius, 2005; Tabuti et al., 2003a; Thomas et al., 2011; Voeks and bin Nyawa, 2006;

forest, and that secondary forest plots yielded 2.7 times the number of medicinal species than plots in primary forest. This was explained by the high representation of disturbed habitat compared to primary forest rather than preference for plants from disturbed habitat *per se*. In Ecuador, herbaceous medicinal plants tend to grow successfully in disturbed areas (de La Torre et al., 2012). Some species appear to actively favour anthropogenic environments (Giday 2003; Giday et al., 2009b). Junsongduang et al. (2013) studied the contribution of medicinal plants from sacred forests and fallows in Thailand, finding that although sacred forest overall housed more species, the two forest types harboured roughly equal numbers of medicinal plant species, meaning that a larger proportion of species were medicinally important in fallows compared to sacred forests, and providing further evidence of the importance of secondary forests in providing medicinal plants in the tropics. Gavin (2009) showed that secondary forests provided more medicinal plants than mature rainforest, because the younger aged forest provided better growing conditions for many medicinal plant species. He concluded that landscapes that incorporate forests of different ages (e.g. structural diversity) will maximise diversity of medicinal plant species.

This is not to say that primary forests do not provide medicinal products. Adnan (2011) found that much higher numbers of medicinal plants were found in old-growth forests in Pakistan, than in re-growth or degraded forests, suggesting that conservation of natural forests is important to retain supplies of medicinal plants. Thomas et al. (2011) found that undisturbed habitats contributed 58% of the 349 medicinal species used by indigenous groups in the Bolivian Amazon. Patches of forest within agricultural landscapes can be equally important for continued provision of medicinal plants (Giday 2003; Ormsby and Bhagwat, 2010). In Tanzania, sacred groves within agricultural landscapes provide communities with medicinal plants (Msuya and Kideghesho, 2009). Ngari et al (2010) found that although the most commonly used medicinal plants were found in disturbed habitats, other species were found in forests and undisturbed riparian zones. Similarly, Giday et al. (2009) found that the majority of species used grew in close proximity to communities but some species were only found in woodlands. Van Andel and Havinga (2008) found that 7 of the 8 most valuable medicinal species harvested for markets in Suriname were collected from forest, and their price reflected the rarity of the species.

Accessibility, cultural practices and perceptions are also important to the choices made by medicinal plant users (Keirungi and Fabricius, 2005). Medeiros et al. (2013) found that people attached greater relative importance to exotic species growing in agricultural landscapes than native species, while Fleuret (1980) found that the majority of medicinal plants used by the Shambaa people were available in anthropogenic zones. Secondary forest or disturbed habitats may provide more medicinal plants as they can be easier to access (Keirungi and Fabricius, 2005; Gazzaneo et al., 2005). Hariyadi and Ticktin (2012) explain that "important medicinal plants should be abundant and easy to find when needed, and weedy species growing in nearby agricultural plots or fallows typically are." It is likely that though all species originated from the forest landscape, many of those species are well adapted to modified environments, while some are likely to be exclusively associated with mature or primary forest, such as large mature trees (Tabuti et al., 2003a; Giday et al., 2009; Keirungi and Fabricius, 2005).

There is *established but incomplete evidence* that medicinal plants with strong associations to mature primary forest are most vulnerable to human disturbance and thus can benefit most from

conservation. However, conservation enforced through limiting access may reduce benefits to people. Because of the high dependency of many poor people in the developing world on medicinal plants, there is a risk of over-exploitation, with effects on healthcare provision (McMullin et al., 2012; Khan and Manzoor Rashid, 2006; Giday, 2003; Hamayun, 2007; Msuya and Kideghesho, 2009; Ndenecho, 2009; Veach et al., 2003; Keirungi and Fabricius, 2005; Yineger et al., 2007). Collection of medicinal products nevertheless has less of an impact than other forest uses (e.g. fuelwood collection, timber extraction) (Khan and Manzoor Rashid, 2006; Veach et al., 2003). Further, the biological characteristics of species and the forms of harvesting also determine how susceptible they are to over-exploitation (Schippmann et al., 2002). Those plants that appear to be available only from native, primary forests are most threatened by disturbance, and it is the provisioning of these species that may be best served by conservation (Khan and Manzoor Rashid, 2006; Tabuti et al., 2003a; Keirungi and Fabricius, 2005; Stræde et al., 2002; Sukumaran et al., 2008).

Many of the studies reviewed here advocate for conservation of biodiversity to preserve these medicinal services (Tabuti et al., 2003a; Ishtiaq et al., 2013a; McMullin et al., 2012; Iqbal et al., 2011; Giday, 2003; Tabuti and Mugula, 2007; Hamayun, 2007; Sorensen and Schjellerup, 1995). Sacred groves in India, for example, have helped to preserve a wealth of medicinal plant species of value to rural communities, even as these species disappear from the surrounding landscape (Khumbongmayum et al. 2005; Sukumaran et al., 2008). Literature identified outside this review also supports this argument. Leaman, for example, states management of medicinal plant resources is essential, though also complex and potentially costly (Leaman, 2008). The literature shows that the benefits of enforcing conservation on the sustainability of these species (and thus the continued provision of the service) can be countered to some extent by the diminished access to local people that enclosure often entails (McElwee, 2010; Gazzaneo et al., 2005). Gazzaneo et al. (2005) found that communities in the Atlantic forests, Brazil, were very dependent on medicinal plants but the majority (82.7%) were either cultivated or collected from anthropogenic zones, because collection of native plants in the adjacent forest was restricted.

The evidence in this review also suggests that domestication and cultivation is another option for retaining provision of medicinal plants, as it may be easier and more reliable than harvesting from forests (Keirungi and Fabricius, 2005; Giday 2003; van Andel and Havinga, 2008; McMullin et al., 2012). However, domestication may not be an economically viable or technologically feasible option for all medicinal products, and it may also have implications for conservation of threatened species if it removes incentives to conserve plants *in-situ* (Schippmann et al., 2002). Further, cultivated versions of the same species can be considered to be of inferior quality, for cultural reasons or physiological differences between wild and cultivated material (Schippmann et al., 2002).

It is *well established* that traditional knowledge is a vital component of medicinal ecosystem services[31]. The use of medicinal plants is firmly embedded in culture, and knowledge of species, their preparations and uses is a resource as valuable as the presence of the species themselves. Conserving knowledge may be just as important as conserving the species themselves (Sorensen and Schjellerup, 1995; Voeks, 2004). For example, Giday, et al. (2009b) found that acculturation of younger generations was the principle threat to continuation of traditional medicine. Changes in

[31] See: Kappelle et al., 2000; Khan and Manzoor Rashid., 2006; Keirungi and Fabricius, 2005; Vijayan et al., 2007; Voeks, 1996; Voeks, 2004.

access to forest species may also threaten knowledge systems and ultimately undermine the provision of medicinal ecosystem services (Gazzaneo et al., 2005; Sorensen and Schjellerup, 1995). Validating and maintaining indigenous knowledge, as well as incorporating it into the design of interventions, are important aspects of conserving medicinal plants.

There are *competing explanations* regarding the role of medicinal plants in income generation through commercialisation. Although in many cases use of medicinal plants is on a subsistence rather than income basis (Kar and Jacobson, 2012), there are examples of varying degrees of commercialisation (Sorensen and Schjellerup, 1995; McMullin et al., 2012; Khan and Manzoor Rashid, 2006; Keirungi and Fabricius, 2005; Hamayun, 2007; Ndenecho, 2009; Ishtiaq et al., 2013a; Sukumaran et al., 2008; Vashist and Sharma, 2013). Indeed, Schippman et al. (2002) made a qualified guess that around 2,500 species of medicinal and aromatic importance (from an estimate of 50,000 total species of medicinal plants worldwide) were being traded on the world market. Commercialisation is viewed as having potential to provide substantial economic benefits (Keirungi and Fabricius, 2005; Vashist and Sharma, 2013; van Andel and Havinga, 2008). However, a number of studies argue that commercialisation poses a threat to biodiversity if harvesting levels are increased above sustainable limits (van Andel and Havinga, 2008), but if implemented well negative impacts can be avoided. Van Andel and Havinga (2008), in a study on commercialisation potential of medicinal plants in Suriname, showed that marketing does not necessarily lead to declining resources and species loss. Jensen and Meilby (2008) showed that higher degrees of commercialisation (access to markets) increased the selectivity of harvest of *Aquilaria crassna* (Agarwood), thereby increasing sustainability. This position is supported by additional literature, such as Karki et al. (2003), who in describing lessons from applying the sustainable livelihoods framework in South Asia, found that medicinal plants could contribute to "biodiversity-based livelihoods" because demand is rising much faster than supply and there are various options for domestication and cultivation.

Fuelwood

The review examined a total of 42 papers related to biodiversity, forest ecosystems and provision of fuelwood.

Wood is the major source of energy for rural communities in the tropical region, particularly in sub-Saharan Africa[32]. According to Matsika et al. (2013), over 70% of the population of Sub-Saharan Africa, predominantly in the rural areas, depend on fuelwood for domestic energy. Studies conducted in Tanzania and Uganda showed that over 95% of rural households used fuelwood as their main source of energy (Njana et al., 2013; Tabuti et al., 2003b). Kimaro and Lulandala (2013) found fuelwood to be the most commonly collected NTFP in Tanzanian coastal forests. Dovie et al. (2004) found that 96% of households harvested fuelwood for domestic purposes in rural South Africa, and in Nigeria 76% of households were found to be dependent on fuelwood for cooking (Ogunkunle and Oladele, 2004). Brouwer and Falcão (2004) showed that in addition to the rural population, the urban households of Maputo in Mozambique are reliant on fuelwood. Matsika et al. (2013) showed that the reliance on fuelwood as energy may continue even after households are

[32] Brouwer and Falcao, 2004; Aabeyir et al., 2011; Dovie et al., 2004; Dyer, 1996; Fleuret, 1978; Goebel et al., 2000; Grundy et al., 1993; Grundy et al., 2000; Hemstock and Hall, 1995; Kijazi and Kant, 2011; Kituyi et al., 2001; Matsika et al., 2013; Naughton-Treves et al., 2007; Ngom et al., 2012; Nkambwe and Sekhwela, 2006; Ogunkunle and Oladele, 2004; Openshaw, 2010; Tabuti et al., 2003b; Vermeulen et al., 1996.

connected to the electricity grid. Tabuti et al. (2003b) also noted that as well as households, local institutions also typically covered their energy needs using fuelwood. Far fewer studies analyse the importance of fuelwood in tropical regions outside Africa. However, fuelwood is considered to be an important source of energy in many areas of Latin America (Aabeyir et al., 2011) and Asia (Miah et al., 2003; Nagothu, 2001; Narain et al., 2008; Aabeyir et al., 2011). Webb and Dhakal (2011) emphasised the importance of fuelwood to the rural populations in South Asia.

As with other NTFPs, poor people are more dependent on fuelwood than those who are better off. In India, dependence on fuelwood was found to decline with increasing income (Narain et al. 2008). Rural households are also typically more dependent on fuelwood, whereas urban populations consume proportionally more charcoal (Kituyi et al., 2001). Nkambwe and Sekhwela (2006) noted that the rural-urban transitional zone is often neglected in assessments of woody biomass use, while many inhabitants of these zones may depend directly on natural resources rather than employment from urban centres. Fuelwood is typically collected for subsistence purposes, and through fuelwood, energy security and associated nutritional security are linked to the availability of forest biomass in the developing countries (Kijazi and Kant, 2011). In addition to subsistence use, fuelwood trade is an important source of income to rural communities in many areas (Openshaw, 2010; Aabeyir et al., 2011).

It is *well established* that pristine forests, degraded forests and areas outside forests are all important sources of fuelwood. The search methods applied did not find a more recent comprehensive global analysis, but de Montalembert and Clement (1983) reported that the importance of natural forests as sources of fuelwood was greatest in Africa and significant in Latin America, whereas in Asia, the majority of fuelwood was derived from areas outside of these forests. Some local studies have attempted to estimate the relative importance of natural forests as sources of fuelwood in Africa. In Malawi in 1996, less than 50% of fuelwood and charcoal was sourced from natural woodlands, with nearly 40% originating from open areas, including farmlands, roadside, grassland and urban areas (Openshaw, 2010). In a study conducted by Hartter (2010) in communities close to the Kibale National Park in Uganda, “natural areas” (forests and wetlands) were reported to be the primary source of fuelwood for 37% of respondents. In Zimbabwe, Grundy et al. (1993) found that 55% of respondents collected their fuelwood mainly from miombo woodland or riverine areas. As compared to other forest products, it is more difficult to estimate the role of protected forests as sources of fuelwood, because its extraction is often regulated or restricted. Illegal collection of fuelwood from protected forests may take place particularly when alternative sources of fuelwood have been depleted (Matsika et al., 2013; Nagothu, 2001; Fousseni et al., 2012).

Several studies suggest that the role of areas outside natural forests as sources of fuelwood is important and increasing in importance. The major source of fuelwood in Uganda was considered to be woodlands outside of forests (Tabuti et al., 2003b). In areas where woodlands do not meet the demand for fuelwood, it is extracted from plantations, windbreaks, avenues and ornamental plantings (Dyer, 1996). Timber processing also generates fuelwood in form of off-cuts and waste (Kituyi et al,. 2001). The importance of farmland trees as sources of fuelwood typically increases with distance to natural forests (Kituyi et al., 2001; Ndayambaje et al., 2013). Farmland trees were considered to form the main source of fuelwood following restricted access to indigenous forests in Kenya (Kituyi et al., 2001). Provision of fuelwood was found to be a major reason for planting trees on farms in Rwanda (Ndayambaje et al., 2013). Natuhara et al. (2012) found that paddy field remnant trees were commonly used as fuelwood in southern Lao PDR.

A variety of trees are used as fuelwood; there is *speculative evidence* that native tree species are more important as fuelwood than exotic species. De Montalembert and Clement (1983) considered native trees to form the main source of fuelwood in Africa. However, exotic trees are also used for fuelwood when available and suitable for burning (Kituyi et al. 2001). Usually, specific tree species are preferred as fuelwood, while inferior quality species may be used when the preferred species are not available (Natuhara et al., 2012; Kituyi et al., 2001). A total of 67 woody species were found to be used for fuelwood in rural communities in South Africa (Dyer, 1996). A total of 75 species were used for fuelwood and 67 species for charcoal making in areas adjacent to a miombo woodland reserve in Tanzania (Njana et al., 2013). In Bulamogi County in Uganda, 48 species were collected for fuelwood; the majority of these were native species (Tabuti et al., 2003b). In western Uganda, Naughton-Treves et al. (2007) found that mainly early successional species growing on fallow land were used as domestic fuelwood, while charcoal production targeted native hardwood species from old-growth natural forests. Some fuelwood trees are also used for multiple purposes. *Acacia nilotica* grown on paddy fields in India is used for fuelwood, fencing materials, construction wood, gum for the confectionery industry, and seeds and fallen leaves for animal feed (Natuhara et al., 2012).

There are *competing explanations* regarding the severity of the impacts of fuelwood collection on biodiversity and the provision of other ecosystem services. In a study conducted in Ghana by Aabeyir et al. (2011), commercial fuelwood collection had led to the depletion of preferred fuelwood species in many areas of wooded savanna. In Bangladesh, illegal harvesting of fuelwood was considered as one of the main threats to the forests (Miah et al., 2011). In Uganda, felling trees for charcoal production was seen as a major threat (comparable with the extraction of timber)to the remaining natural forests outside parks and reserves (Naughton-Treves et al., 2007). In Senegal, the most important fuelwood species were reported to be also felled for commercial purposes (Ngom et al., 2012). Fuelwood collection by local people has been linked to the loss of natural forests also in India (Nagothu, 2001).

However, the impact of fuelwood harvesting is often less severe than assumed from the amount of biomass collection. This is due to two factors. Firstly, when available, fuelwood is typically collected from dead wood material or fallen branches (Ektvedt, 2011; Nagothu, 2001; Matsika et al., 2013; Tabuti et al., 2003b). Nagothu (2001) estimated that three quarters of wood collected by rural people in India consisted of dry wood picked up from the ground. A system of Joint Forest Management (JFM) allows local people to collect dry and fallen branches for fuelwood, and access wood removed during thinning operations. This kind of system was reported to help to maintain forests with a favourable composition of species for the collection of fuelwood (Narain et al., 2008). However, Dovie et al. (2004) noted that the decreased availability of dead wood may lead to increased tree felling. Local populations may also adapt to decrease of fuelwood resources by switching to the use of alternative fuels or using more efficient stoves. According to Miah et al. (2003), the fuelwood shortage in Bangladesh has led to compensation strategies including fuel storage, reducing the use of fuel, and replacing wood fuel with agricultural residues. In areas where lumber industry provides wood residue, this may form a major source of fuelwood for local households (Browder, 1989).

The improved management of forests and woodlands, the use of fuel efficient stoves and the planting of fuelwood species are recommended to prevent the loss of fuelwood resources. Improved woodland management is seen as an important means to mitigate the degradation of fuelwood resources (Tabuti et al., 2003b). Dovie et al. (2004) pointed out that although the livelihoods of many rural people are dependent on direct use values of biodiversity, conservation policies tend to place little emphasis on species used for fuelwood. Jagger et al. (2005) found, in a study comparing different systems of woodlot management in Ethiopia, that restrictions to the harvesting of some species limited the income from woodlots, a trade-off with mitigating the loss of biodiversity. Nagothu (2001) noted that limiting the access of the rural population to the remaining forest resources was not a successful method of conservation. The planting of fuelwood species is also commonly recommended as means to improve the sustainable use of the resource (Tabuti et al., 2003b; Miah et al., 2003; Webb and Dhakal, 2011).

Part 2. Lessons for the ICF forestry component and other forest-related interventions

Biodiversity plays a role in supporting important ecosystem services associated with tropical forests and of concern to the ICF forestry component: carbon storage and the resilience of carbon stocks; other regulating services, and provisioning services. The review highlights that there is evidence for important relationships between different aspects of biodiversity, such as species richness, species identity and ecosystem intactness, and the ability of ecosystems to provide services. However, the types and strengths of these relationship and mechanisms through which they operate vary. There is stronger evidence for the role of intact, natural forests, in the provision of important ecosystem services, than for variability in species richness within intact natural forests impacting provision of ecosystem service.

2.1 Summary of main review findings

In terms of carbon storage, globally there is a positive correlation between species richness and carbon stocks, and there is strong evidence that the carbon stocks of intact forests are more resilient than those of degraded or fragmented forest. However, within tropical forests, there is less correlation between spatial patterns of carbon stocks and biodiversity of undisturbed forests and the patterns are complex.

There is generally a well established link between tropical forests and the provision of the locally and globally important regulating services considered by this review. For example, there is strong evidence of the roles played by forests in reducing soil erosion, regulating water flows, purifying water supplies, regulating microclimates and providing protection from natural hazards, such as landslides and floods. There is also evidence of a link between mangrove forests and the composition and value of fish catches. There are varying levels of confidence in the relationship between biodiversity *per se* and regulating services. There is evidence of a link between species richness and the prevention of human and animal diseases. The literature also supports a well established link between pollination services and species richness and identity, with proximity to forest as well as species abundance playing a role in the effective pollination of crops.

Among the provisioning services, the review shows that while pristine forests are the main source for many tropical timber species and their exploitation plays a role in providing incomes for local people, timber provisioning services can also be derived from disturbed forests, plantations and agroforests. Further, timber extraction can change the species composition in tropical forests and reduce the long-term availability of the resource.

Forests are clearly an important source of NTFPs for communities in tropical regions, and that forests with high species richness provide a wider range of NTFPs. Wild foods play a vital role for people in many tropical countries, diversifying their diets and livelihoods and supporting food security, particular during periods of hardship. It is well established that a wide variety of biological resources is linked to maintaining this food security, although secondary forests, degraded forest lands and mosaic landscapes appear to be as important for this provisioning service as pristine, intact forests. It is also well established that the many species of wild plants play an important part in the provision of fodder for livestock in rural communities.

In addition, this review has shown that tropical forests, and the biodiversity of these forests, make a major contribution to the primary healthcare of indigenous and rural communities, as well as for the development of conventional medicines. As with food security, there is evidence that species richness confers redundancy, where multiple products can be used for the treatment of a condition. Similar to other provisioning services, it is also well established that secondary forests and disturbed habitats provide a considerable proportion of medicinal plants, but that medicinal plants found in pristine, natural forest are most vulnerable to disturbance and may benefit most from conservation measures. As with other types of forest products, access forms an important mediating factor, although cultural practices and traditional knowledge are also vital components of medicinal ecosystem services.

Similarly, fuelwood, the major source of energy for rural communities in tropical countries, especially in sub-Saharan Africa, is extracted from both pristine forests and areas outside these forests, such as degraded forest land. However, a variety of species are used for fuelwood, and there is some evidence that native species are more important in this role than exotic species. For timber, and NTFPs both the provision of the service and the impacts of harvesting on biodiversity and other ecosystem services are mediated by the level of access communities have to forests and the management regime for resource use.

2.2 Lessons for the forestry component of the ICF

The findings of this review provide lessons for the forestry component of the ICF, with implications for the higher level approach taken in selecting and designing interventions, as well as specific considerations related to types of interventions in the forestry sector.

- This review indicates that biodiversity and its conservation have value beyond a 'side benefit' of forestry interventions – it is of fundamental importance in achieving the primary objectives of the ICF, through its role in enhancing, sustaining, and restoring the provision of other ecosystem services of direct consequence to human wellbeing. If safeguarding biodiversity is thus considered to be a priority objective of future ICF interventions, then it should also be measured and monitored explicitly.

- Aspects of biodiversity can also reasonably be considered as important to the adaptation and resilience component of the ICF. The findings of the review strongly suggest that intactness and naturalness in tropical forests, as well as the redundancy provided by a diversity of biological resources, confers a greater degree of resilience to environmental change and stress, both for ecosystems and the communities that rely on them, including to climate change, compared to low biodiversity, degraded and fragmented forest.

- Measures to conserve intact, natural forest, and to restore degraded areas to near natural levels of intactness and diversity, are likely to be broadly effective at preserving both carbon and ecosystem services that benefit local populations (subject to issues of access and use rights). It is not yet clear for all ecosystem service types whether, within natural and intact forest, more biodiverse areas will provide more services. This is partly because there are generally fewer people living near less disturbed forests (see Box 2 on *disturbance*), and partly due to a lack of evidence of a relationship.

- The carbon storage, biodiversity and ecosystem service benefits of forests are best understood at the landscape or even regional level. For example, this review has shown that landscape-level diversity may contribute to resilience (e.g. to climate change), by mitigating the impacts of disturbances. People also use a variety of forest types and other ecosystems in the landscape, such as pristine, secondary and cultivated forests, to meet different needs. In addition, this review has highlighted the importance of access and proximity to communities in mediating the value of particular ecosystem services, and this may influence the locating of interventions. For example, if continuous mature forest is the end goal of forest policy, medicinal and food plants that grow better in disturbed habitats (whether natural or anthropogenic) will decrease in abundance (Giday et al, 2009a). Forestry interventions are therefore best planned at the landscape or regional level, taking into account the multiple needs of communities and potentially utilising spatial planning tools, in order to maximise the synergies between different objectives and to minimise risks.

- The review has shown that the use of biological resources by communities is often associated with particular types of knowledge, cultural practices and preferences. Interventions aimed at enhancing the benefits to livelihoods and the sustainability of ecosystem services should therefore recognise and make use of the role played by traditional and community knowledge and practices.

- The literature examined in this review mainly represents the evidence for general theoretical relationships and does not cover in detail specific impacts of interventions based on local circumstances. There is scope for a more in-depth review of the practical experiences gained through the implementation of interventions in tropical forests and factors potentially linked to success, including the experiences of the ICF so far. This may contribute to the development of guidance to support decision-making about the choice of interventions and implementation approaches in particular locations.

In the following section, we explore in greater detail the potential trade-offs and synergies for biodiversity, carbon storage and other ecosystem services related to some specific types of interventions in tropical forests, particularly those associated with REDD+ activities. The interventions discussed are presented in three categories: interventions for improving agricultural practices; interventions for protecting forests and/or reducing degradation; and interventions for afforestation and reforestation.

The table provided in Annex 3 summarises the potential positive and negative impacts, and interactions between these, for each intervention. It is important to note that: a) the list of interventions is not exhaustive, but limited to those often referred to in REDD+ and FLEG activities[33]; and b) that the balance between trade-offs and synergies[34] depends significantly on the methods used for interventions and the previous land use. Further, although we have predominantly referred to potential negative and positive impacts, there is also the issue of *effectiveness.* Particular interventions may have issues associated with them which may affect whether or not they meet their objectives.

[33] Interventions based on activities in listed: Kapos et al. (2012); Miles et al. (2010b); and Epple and Thorley (2012).
[34] For the purposes of this report, the term synergy is understood to refer to a range of positive interactions, from complementary benefits up to full synergies, where the interactions between one or more elements produce a combined effect greater than the sum of their separate effects.

2.2.1 Interventions for improving agricultural practices

A) Increasing productivity of agricultural land
Aim: Increase yields and efficiency in order to potentially decrease conversion/degradation pressure on forests and other natural ecosystems

Potential contribution to achieving ICF objectives: Increasing agricultural productivity and yields is recommended in the context of REDD+ as an action to reduce deforestation on the basis that increasing yields on currently used agricultural land can help to meet agricultural demand on a smaller land area. This is referred to as a 'land-sparing' approach. The potential impacts of this approach heavily depend on how the intervention is implemented, the previous land use, how it interacts with other measures and trends in the landscape (e.g. whether protection increased for standing forest elsewhere), and the scale over which the impacts are considered (e.g. only locally or beyond the agricultural areas).

Potential positive impacts/synergies: In a well-implemented land sparing approach, there is the potential for increases in yields and efficiencies that translate into improved livelihoods and food security (Jackson et al., 2012), while simultaneously reducing losses in standing forests. In addition to preservation of carbon stocks, the retention of forest in an agricultural landscape, may help to retain biodiversity and associated ecosystem services such as pollination that increase agricultural yields (see section 1.2.5 on pollination) and benefit local livelihoods (for example, through the provision of NTFPs, see section 1.3.2). Any resulting 'sparing' of forest land from conversion or degradation elsewhere will have benefits for the protection of biodiversity, carbon storage and other ecosystems services in those standing forests. The ability of this approach to achieve noticeable effects on forest conversion pressure strongly depends on the scale at which methods can be introduced, how effective these methods are at increasing revenues and the sustainability of agriculture in those lands, and whether the risk of increasing the demand for land for agriculture can be mitigated, which may be achieved through complementary forest protection measures in the landscape/region (see below).

Potential negative impacts/trade-offs: The increase in agricultural yields and the potential conservation of remaining forests often trades off against significantly reduced biodiversity, carbon storage and other ecosystem services within intensively farmed areas. Such impacts, including the effects of increased chemical use on biodiversity on-site and downstream, may have important consequences for the achievement of ICF objectives, through reducing the provision of ecosystem services important for food production (e.g. pollination, protection from natural hazards, see section 1.2) and local livelihoods (e.g. NTFPs). There is also a risk that by making agriculture more profitable and attractive this strategy may in fact increase demand for land. Further, the achievement of the positive effects from increased yields are likely to be mediated by socio-economic factors, such as commodity prices and changes in the tenure and access rights of smallholders to farmland and other natural resources. Without social safeguards such as secure land rights there is a risk of land appropriation from smallholders.

Note: For the agricultural interventions that attempt *to reduce deforestation by increasing farmer satisfaction with existing agricultural land* (Interventions A, B, and C), an important safeguard is the use of protection interventions for standing forests (Interventions F & G) to reduce the risk of negative impacts including increased demand for land.

B) Sustainability improvements to small- and large-scale conventional or traditional agriculture

Aim: Increase profitability and sustainability of small- or large scale conventional/traditional agriculture to potentially decrease forest conversion pressure, as well as reducing negative on-site impacts

Potential contribution to achieving ICF objectives: Improvements to agricultural practices in the tropics aim to reduce pressure on forests by removing or reducing the need to repeatedly clear or access new areas for crop cultivation and livestock grazing (i.e. 'slash and burn'). Such methods, though practiced for many thousands of years and sustainably practiced where soco-economic pressures are low, are in the present context of increasing population and demand for agricultural produce not conducive to REDD+ priorities. Although tropical forest soils are notoriously nutrient poor after slash and burn cultivation, improving the viability of currently farmed areas can be achieved through a number of ways. One example is the introduction of integrated organic agriculture, which retains greater soil fertility and biomass.

Potential positive impacts/synergies*:* This approach has the potential to deliver multiple positive impacts for biodiversity conservation, carbon storage and other ecosystem services, while increasing incomes for farmers, and thus crucially improving farmer satisfaction. A major strength of this approach relative to agricultural intensification is its ability to provide on-farm ecosystem services, particularly increased carbon stocks and other regulating services, though the actual flows of these services will depend upon field-scale decision-making. Avoiding chemical inputs and fire as much as possible will increase biodiversity (Tuck et al. 2013). Also, benefits may extend to locations further afield, such as in downstream watersheds (e.g. sediment and pollution reduction). Timber and fuelwood benefits may depend on whether the intervention includes agroforestry or woodlots, but some timber and fuelwood supply might be expected from start of fallow periods. According to this review, the synergistic effects of biodiversity conservation (such as increased species richness and abundance) may increase the resilience of provisioning services including food production, timber, fuelwood, food and medicinal products, as well as regulating services (such as pollination) that support agricultural production. Increased revenues from organic or conservation agriculture, especially if certification or price premiums can be achieved[35], may lead to direct livelihood benefits. Any resulting 'sparing' of forest land from conversion or degradation elsewhere will have benefits for the protection of biodiversity, carbon storage and other ecosystems services in those standing forests. The ability of this approach to achieve noticeable effects on forest-conversion depends on the same factors considered for Intervention A.

Potential negative impacts/trade-offs: Increased profitability of agriculture carries a risk of inadvertently increasing forest conversion pressure (Tuck et al, 2013). Also, conversion to organic agriculture can lead to decreased productivity, particularly in the short-term, where the alternative is high-input agriculture (but not to conventional agriculture on degraded land). This could

[35] Some certification schemes, such as Rainforest alliance certification, include social provisions such as labour standards which will also provide benefits for local communities (Sustainable Agriculture Network, 2014).

undermine profitability and thus the ability to provide incentives not to convert new land. At the other end of the spectrum, increased economic benefits from conversion to organic agriculture or improved pastures for livestock may increase demand for agricultural land. Further, this approach requires substantial investments in funds, time and ongoing support in order to improve yields through small-scale technologies, as well as human capital requirements (knowledge networks, learning). In addition, if chemicals are used to increase yields, on-farm and downstream biodiversity and ecosystem services benefits are likely to be reduced. As mentioned above, protection measures may help to safeguard forest conversion in combination with this indirect, demand-side approach.

C) Conversion of agricultural land to agroforestry systems

Aim: Increase in-situ benefits of increased tree cover in agricultural areas, and reduce pressure on forest ecosystems

Potential contribution to achieving ICF policy objectives: The conversion of agricultural land to agroforestry systems can result in increased biodiversity, carbon storage and other ecosystem services in agricultural areas through increased tree cover, as well as potentially reducing pressure on standing forests for resource extraction (e.g. timber and fuelwood). The relative biodiversity and carbon sequestration benefits of agroforestry systems depend on the previous land-use, the approaches used and the impacts of the conversion process (Miles et al., 2010b; Miah et al., 2011). The impact on biodiversity, food production and livelihoods also depends considerably on the species used and the management regime.

Potential positive impacts/synergies: Depending on the management regime and species used, agroforestry has the potential to provide increased biodiversity, carbon storage and regulating and provisioning ecosystem services. Some agroforestry systems have been shown to support high levels of biodiversity, depending on the species used. Increased tree cover as well as increased diversity of planted species are likely to lead to improved resilience (to climate change but also for periods of hardship), as well as enhanced regulating services (such as pollination, erosion control and water regulation) and improved provision of NTFPs and timber. Local livelihoods may benefit from improved ecosystem services, as well as from the diversification of incomes. If successful in increasing incomes from agriculture, this approach may also lead to reduced conversion pressure.

***Potential negative impacts/trade-offs**:* Systems using mainly non-native, fast-growing timber species may have greatly reduced biodiversity. Extensive agroforestry systems seeking maximum profitability are likely to trade off increased incomes against lower biodiversity, carbon storage and ecosystem service benefits. Likewise, maximising biodiversity and ecosystem services will likely reduce profitability. In addition, the impacts on biodiversity, carbon sequestration, food security and local livelihoods depend on the specific conversion undertaken (e.g. the previous land cover, crops being produced, and how the conversion process may have affected biodiversity, land tenure and access to natural resources) as well as market access and the ongoing support, such as extension services, available to smallholders.

2.2.2 Interventions for protecting forests and/or reducing degradation

D) Establishing or reinforcing strict protected areas (i.e. IUCN class I, II)

Aim: Maintaining existing natural forest by preventing access and use of forest resources and land conversion

Potential contribution to achieving ICF objectives: Measures to conserve intact natural forest, such as establishment or reinforcement of protected areas are likely to be the most effective strategy to preserving biodiversity, carbon stocks and some types of ecosystem services that benefit local and downstream populations.

Potential positive impacts, with potential for synergies**:** If forest areas are otherwise under threat from deforestation and degradation, strict protection in PAs is likely to protect carbon storage, biodiversity and other regulating services (such as soil erosion control, water and climate regulation, and protection from natural hazards). Thus, the success of protected area management depends on location, as well as management regimes and other site-specific features. Protection may also benefit provisioning services, e.g. for food production, through protection of source populations or key ecosystem services. For example, protection of mangroves may have benefits for fisheries (see section 1.2.7). As such, livelihood benefits from PAs depend on the careful inclusion of local communities in decision-making processes, and especially benefit-sharing mechanisms to alleviate negative impacts. The degree of co-benefits from this strategy depends on the spatial congruence of these ecosystem services and the PA location related to beneficiaries, such as downstream communities. A likely synergy of conserving biodiversity and retaining intact and natural forest is the increased resilience to climate-related disturbances, essentially providing a means of insurance against future uncertainty or instability caused by climate change.

Potential negative impacts/trade-offs: Strict protection of forests often leads to a reduction in provisioning services. Strict protection may trade-off the benefits of protecting carbon stocks, biodiversity and regulating services with negative impacts on the supply of provisioning services, such as timber and fuelwood extraction, if restrictions are placed on access by resource-users. In some cases it may have mixed effects on food production and medicinal products. There is also a risk that restrictions may increase pressure on other ecosystems. Further, there is the potential for increased human-wildlife conflict if biodiversity conservation results in greater numbers of some wildlife species. Protected areas are also very expensive in terms of operational and opportunity costs, particularly if pressure to utilise resources and or convert to other land uses is high.

E) Community forestry (relative to strict protected areas)

Aim: Reducing deforestation and forest degradation through the promotion of community forestry or joint forest management (including for the production of timber)

Potential contribution to achieving ICF objectives: Community forestry or JFM approaches involve the full or partial devolution of forest management authority to local communities, with the aim of fostering more effective forest management, biodiversity conservation, and livelihood benefits. There is mixed evidence concerning the benefits of community forestry approaches for biodiversity conservation.

Potential positive impacts/synergies: By successfully implementing community-based management, carbon storage, regulating services and livelihoods benefits can be achieved. A recent meta-analysis showed that community forestry approaches can effectively meet conservation and livelihood policy objectives. Larger forest size and greater autonomy at the local level are associated with high carbon storage and livelihood benefits (Chhatre et al., 2009). In terms of ecosystem services, community forest management can be an effective strategy in maintaining flows of provisioning services. Regulating services are also likely to better maintained in effective community forestry projects than degraded forest, as forests are more likely to have higher intactness and naturalness. Community managed areas can also help to maintain cultural services, with the added benefit of conferring legitimacy (Bowler et al., 2010.) If community management can increase the legitimacy of forest protection and decrease conflict, its outcomes may exceed those of a poorly managed PA.

Potential negative impacts/trade-offs: The effect of this strategy on policy objectives, such as carbon storage or the preservation of particular ecosystem services depends on the management system implemented (Montoya and Young, 2013) and the previous land use regime in place. Increased income from forest products may encourage unsustainable harvesting/extraction; significant investments in capacity building, training and support for enforcement may be required. Compared to strict protection, community managed forests may be less effective for protecting biodiversity of high conservation value (although they may be very effective for certain valuable species, e.g. medicinal plants), and for maximising regulating ecosystem services.

F) Reduced impact logging (relative to conventional logging)

Aim: Improve forest condition and carbon storage in forests by limiting damage to vegetation and soil during timber extraction

Potential contribution to achieving ICF objectives: As noted by Thompson et al. (2012), large areas of tropical forests lie outside of protected zones and are either being logged or are likely to be logged in the future. Conventional or poorly managed logging practices often result in the loss or damage of 10-20 trees for each tree felled in tropical forests, and logging may be followed by other types of disturbance (e.g. hunting, shifting cultivation) (Kapos et al., 2012). Improved forest management in timber concessions is therefore an important strategy for reducing forest degradation.

Potential positive impacts/synergies: By employing RIL strategies, positive effects on biodiversity conservation over the long-term as well as carbon stock and ecosystem service benefits may be achieved, provided RIL techniques are implemented comprehensively and with consideration of other measures in the landscape. Reduced impact logging (RIL) techniques, such as reducing harvesting intensity, managing access to forest concessions and using careful directional felling, can reduce collateral damage to vegetation and soil. RIL results in far less structural damage, and fewer changes to biodiversity (e.g. alterations to species abundance and composition). Furthermore, the total net benefits from RIL may emerge in the long-term, after logging has ceased, even if immediately unclear. The regulation of activities associated with logging is also likely to have positive impacts on biodiversity, for example by reducing hunting pressure. RIL may reduce carbon emissions from logging, depending on comprehensive implementation. In terms of ecosystem services, the findings of this review would indicate that measures that lead to less damage to vegetation, an improvement in naturalness and intactness of standing forests, and maintained or enhanced species richness would be linked to increased provisioning and regulating ecosystem services. To maximise benefits RIL techniques should be applied as a package of measures covering the pre-, during and post- logging periods and at the landscape scale (Kapos et al. 2012). Higher costs of extraction may be offset by achieving a price premium for the timber (e.g. through certification).

Potential negative impacts/trade-offs: The trade-offs associated with RIL interventions include the higher cost of implementation (compared to conventional logging), and the overall negative effects on carbon storage and biodiversity of the logging activities relative to no disturbance. Additionally, the precise effects depend on how RIL is implemented; for instance, as flows of ecosystem services ultimately depend on the presence of beneficiaries, any potential increase in flows of ecosystem services caused by RIL depends on access for local communities, particularly for provisioning services (as these tend to require direct contact, while regulating services can be produced much further from the eventual beneficiaries). Hence, the utility of these services to communities would be mediated by levels of access.

G) More sustainable harvesting and/or alternative production of NTFPs

Aim: Improve forest condition and carbon storage in forests by limiting damage to vegetation and soil during NTFPs extraction

Potential contribution to achieving ICF objectives: Reductions in harvesting pressure may be achieved through introduction of more sustainable management regimes, relative to conventional harvesting, or through the replacement of NTFP-dependent livelihoods with non-forest alternatives. Cultivation of medicinal plants, horticultural kitchen gardens, and farm woodlots are all examples of reducing demand for NTFPs from primary forest by providing the species of use elsewhere.

Potential positive impacts/synergies: For alternative NTFP production projects, if projects and schemes do succeed in reducing demand from forests, significant benefits for biodiversity, carbon stocks and provision of ecosystem services (particularly regulating services) can be expected. Similar benefits can be expected for introduction of sustainable management regimes, if such management approaches are developed in partnership with communities, achieving legitimacy and greater ownership by the people in question. Such benefits are likely to emerge in the long term and positive responses from the ecosystem may take time to emerge. If communities can collaborate on producing such management approaches, and the resulting access restrictions are equitable, transparent and lead to tangible benefits, there are likely to be social benefits as well, such as increased community cohesion and empowerment.

Potential negative impacts/trade-offs: Depending on the management approach, continued extractive use is likely to prevent levels of carbon storage, biodiversity, and potentially flows of some ecosystem services from reaching their maximum. Further, the costs of enacting sustainable management practices may be higher than unregulated extraction, and introduction of alternative production of NTFPs may require time and resources for adequate capacity building to ensure success (alternative production schemes often fail for lack of capacity and resources). Also, if alternative production of NTFP is successful enough to increase incomes and/or demand, this may increase pressure for the same commodities from their original forest locations and elsewhere. There is commonly a temporal trade-off when sustainable management regimes are enacted between the prolonged supply of the ES into the future against the need for continued levels of supply in the present. In particular, some resource-users will be very dependent on the immediate use of the resource and the imposition of a sustainable management approach can harm their wellbeing. In such cases, payments for ecosystem services (PES) may be a useful complementary approach.

H) Fuel substitution/efficiency
Aim: Reduce forest degradation and deforestation through substitution of fuel sources and/or reducing demand for fuelwood through improved cook stove technologies

Potential contribution to achieving ICF objectives: This intervention aims to reduce the need for fuelwood from natural forests by increasing the efficiency by which such fuelwood is burned, or replacing fuelwood with an alternative fuel source (e.g. plantation fuelwwod, green charcoal, non-wood fuels).

Potential positive impacts/synergies: By increasing efficiency or substituting wood, a number of different benefits can be expected in line with the reduced degradation on standing forests, including biodiversity conservation, increased carbon storage, provision of ecosystem services and livelihoods benefits, depending on the effectiveness of the scheme in reducing demand or providing viable alternatives. The preservation of biodiversity (e.g. species abundance, richness and composition) as a result of reduced forest degradation can be expected to have synergistic effects for the provision of these services, including increased and more stable flows of ecosystem services, and resilience to climate-related disturbances (see mechanisms described in section 1.1). Also, by improving the use of fuelwood and reducing the amount needed, workloads and air pollution in households may to also be reduced.

Potential negative impacts/trade-offs: Success in delivering benefits is likely to depend on the capacity of the cookstoves or new fuel sources to meet the needs of users, the efficiency with which they burn fuel, as well as the scales at which cookstoves or alternatives can be rolled out. A substantial upfront trade-off of using improved cookstoves is the cost of materials and installation. If fuels for substitution are more expensive than fuelwood, which may be freely acquired, incentives will need to be provided to encourage use of such fuels, including subsidies. Furthermore, some communities may have cultural attachments to certain ways of cooking/heating and imposition of new stoves may be unpopular, discouraging uptake and thus effectiveness of the scheme.

I) Appropriate forest fire management
Aim: Reduce forest degradation through management of forest fire regimes

Potential contribution to achieving ICF objectives: Forest fires at frequencies and/or intensities that deviate significantly from 'natural' levels can adversely affect the intactness and health of forest ecosystems, with dramatic impacts on carbon stocks, ecosystem services, and livelihoods, and can in the worst cases lead to conversion of the ecosystem to less desirable states such as scrubland. Appropriate fire management is likely to have considerable benefits if measures are effective enough to reduce forest degradation and conversion.

***Potential positive impacts/synergies**:* If fire management prevents forest degradation or conversion and reduces uncontrolled fires it is likely to provide substantial combined benefits for carbon storage, biodiversity and ecosystem services, and therefore indirectly for human wellbeing, by helping to maintain forest structure, composition and function. Forests frequently affected by disturbance tend to contain less biomass so reducing fires can lead to carbon emission reductions and stock benefits, as well as timber and fuelwood benefits. In addition to contributing to biodiversity conservation, the maintenance of forest structure and composition is also likely to enhance soil protection and hydrological services regulating water flows and quality. Maintaining or increasing biodiversity (e.g. species richness) could also increase resilience to climate change, which may feedback beneficially to limit the damage caused by future fire regimes.

***Potential negative impacts/trade-offs*:** Livelihoods may be affected if efforts to manage or reduce fires reduces the availability and/or quality (e.g. through loss of fertility enhancing ash input) of land for shifting cultivation or plantations. Limiting fire may also limit the availability of species that respond favorably to fire (such as in dry forests that naturally burn), some of which may be important for local use (e.g. medicinal or food species). Local concerns about the negative effects of fire, or preferences for certain fire regimes, can also influence community reactions to fire regulation. A further key consideration is that for some ecosystems naturally burn. they are well adapted to fire. At the species and ecosystem level, the system may be remarkably resilient. In these situations, fire management that leads to extended return times can cause fuel loads to build up, increasing the damage when the fire does eventually come. Thus, fire management should be only considered when the background fire regime is well understood.

J) Hunting regulation (relative to uncontrolled wildlife hunting)
Aim: Improve the sustainability of wildlife hunting and bushmeat extraction and associated effects on forest structure and composition

Potential contribution to achieving ICF objectives: Approaches that aim to reduce the impacts of hunting pressures on animals used for bushmeat, medicines or other purposes can have direct positive effects on wildlife populations, particularly those of conservation value, as well as indirect benefits for other policy objectives such as carbon storage and other ecosystem services, and in the long-term, livelihood benefits.

Potential positive impacts/synergies: Regulation of hunting can have positive impacts for biodiversity directly (e.g. on species abundance), as it is well established that bushmeat hunting can have dramatic effects on target species. This effect depends on the life-history characteristics and resilience of the species being harvested. While rarer and more sensitive species are likely to disappear quickly after hunting begins, some other mammals, particularly those which reproduce often, can sustain higher levels of hunting for longer time periods. Regulation can also benefit biodiversity indirectly, by reducing damage to other species and degradation of forest ecosystems more broadly caused by the loss of key species. Removal of top-predators can affect food chains, causing changes in the relative abundance of other animals and plants. For example, the removal of wolves in Scotland has been widely reported as contributing to the explosion in deer numbers, preventing the natural regeneration of woodlands. Reductions in species which contribute to seed dispersal and disturbance functions (including large animals like elephants and rhinos) can negatively affect plant regeneration. The effects of reduced fauna on ecosystems and biodiversity more broadly have significant consequences for other policy objectives, as altered structure and composition affects carbon storage capacity, as well as the ecosystem services, such as the provision of other food and medicinal services. Thus, imposition of sustainable harvesting approaches can ensure longer-term provision of ecosystem services and livelihood benefits from forests. Improving the sustainability of bushmeat harvesting also has the potential to ensure a longer-term supply of an important food source for local communities, as well as improve the governance and transparency of natural resource use. Hunting licenses may offer a funding stream for communities or the management of reserves.

Potential negative impacts/trade-offs: Depending on which species are targeted for regulation and whether substitutes or alternative livelihoods are promoted, this intervention may reduce the overall meat supply and have important consequences for the livelihoods and well-being of hunting-dependent communities. In addition, the effectiveness of hunting regulations will depend on the willingness of communities to restrict these food and income sources, perceptions of equity in the implementation of restrictions, and the capacity to enforce regulations locally and potentially against outsiders.

2.2.3 Interventions for Afforestation/Reforestation

K) Monoculture plantations (afforestation with tree crops of non-native species on non-forest land)
Aim: To quickly expand forest cover on non-forest land, increasing carbon sequestration and providing other forest-related services

Potential contribution to achieving ICF objectives: As much as 2 billion ha of land are estimated to be available globally for forest restoration, reforestation and afforestation approaches, mostly in tropical and temperate regions (Minnemeyer et al., 2011).

Potential positive impacts/synergies**:** Afforestation using non-native species on non-forest land may lead to improved carbon storage and there are likely to be increased timber and fuelwood supplies. Plantations of non-native species have been found to develop a closed canopy and accumulate biomass more rapidly than in natural regeneration processes (Aide et al., 2000). Long return timber harvests can sequester and store carbon for long periods. This may reduce pressure for woody biomass from standing forests and thus have the synergistic effect of reducing pressure to convert natural forests. Monoculture plantations on degraded land can however deliver important benefits in terms of provisioning services, such as timber and fuelwood, and regulating services associated with forest cover, such as rapid gains in regulation of water flows and quality, depending on the species and inputs used (but see potential trade-off below). Further, even monocultures can enhance species richness on barren land, by matching planted species to a site, creating canopy cover and altering the microclimate and conditions to attract wildlife. The plantation techniques applied and their effects on carbon, biodiversity and the provision of ecosystem services (at the site and the landscape level) will ultimately be determined by the objectives of the intervention and local ecology.

Potential negative impacts/trade-offs: The contribution of such plantations to conservation should be considered in light of previous land uses (e.g. whether it is replacing severely degraded land), but they are likely to have relatively low value for biodiversity conservation. The overall function of the forest is also likely to be limited by the management approach. Although monoculture plantations may have biodiversity benefits compared to severely degraded land, they are generally considered less beneficial for biodiversity than other strategies. They may also have a number of negative impacts beyond the presence of biodiversity within the plantation. For example, non-native plantations may alter species composition in other, nearby forests through the spread of invasive species, pests and diseases. In the short-term, afforestation with monocultures can restore regulating services faster than other interventions (e.g. assisted natural regeneration, ANR), although there are many examples where forests of non-native species have negatively affected local soil and hydrological functions, and this has ultimately negatively affected the persistence of the forest itself. There is some evidence that certain plantation types reduce stream flows, for example (Jackson et al., 2005). Soil erosion can remain problematic where an understorey of vegetation is lacking and the long-term outcome for soil quality is relative poor compared to other approaches (Miles et al., 2010b). The homogeneity of monoculture plantations is likely to result in less habitat availability for native species and lower resilience to environmental stress. Replacing agricultural land or secondary forest can also negatively affect provisioning ecosystem services, unless social provisions are taken into account.

L) Mixed plantations (tree crops of mixed, native species on non-forest land)

Aim: To expand forest cover on non-forest land, increasing carbon sequestration and providing other forest-related services, using methods more likely to achieve co-benefits

Potential contribution to achieving ICF objectives: Afforestation of non-forest land using mixed plantations managed for multiple benefits is an important strategy for meeting ICF and REDD+ objectives.

Potential positive impacts/synergies: Because plantations develop a closed canopy and accumulate biomass more quickly than natural regenerating forests carbon and provisioning services objectives (particularly timber) can be achieved faster than natural reforestation activities. Also by using mixed species plantations, a number of extra benefits can be achieved simultaneously. Utilising a wider number of native species is likely to have better outcomes for biodiversity conservation, compared to both the previous land use (if agricultural land but not if pristine natural land) and monoculture plantations, particularly where native species are used to increase structural diversity and thus increase habitats (Epple and Thorley, 2012). As with other types of afforestation, mixed plantations of native species on non-forest land can provide significant benefits for carbon sequestration and storage. Mixed plantations are also more likely to have greater resilience to climate change and disease, and reduced risk of contributing to the spread of invasive species (Miles et al., 2010b). Mixed plantations can support regulating services, such as improving soil quality, increasing pollinator activity, and regulating water flows and quality, depending on the condition of the site and management measures. For example, managing for structural diversity will help to develop a litter layer and potentially an understorey, which help to limit erosion. Compared to non-forest, degraded land (but not necessarily secondary forests or disturbed habitats) and monoculture plantations, they have the potential to provide a range of NTFPs, including medicinal plants, as well as fuelwood and timber, to local communities (although this depends on the access afforded by the management regime). Given higher biodiversity (with increased complementarity and niche differentiation between species), timber yields could in theory approximate those of monoculture (see sections 1.2.2 on productivity and 1.3.1 on timber). Depending on the management type and access rights, there may be increases in other provisioning services such as food and medicinal plants, although the net benefits depend greatly on the previous land-use. Increases in timber and fuelwood supply from plantations may reduce pressure to exploit natural forests. Synergies can also be conferred by the higher biodiversity, which is expected to make the forest more resilient to climate-related disturbances and provide more stable regulating services, compared to monocultures.

Potential negative impacts/trade-offs: Plantations of native species present a trade-off as the rate of growth will likely be slower than some plantations of non-native species (Aide et al., 2000). The increased biodiversity and adapted management techniques for native plantations also involve trade-offs in terms of higher costs of implementation, as well as potentially lower growth and survival rates compared to plantations. As regulating service provision depends on management of the understorey and soil, managing for these ecosystem services may have to be traded-off against maximum possible timber and NTFP extraction. Furthermore, impacts on biodiversity depend on previous land use as there is a risk of converting non-forest ecosystems of high conservation importance to plantations. Also, there may be reductions in provisioning ecosystem services as many NTFPs (particularly medicinal plants) are found in fallow or degraded areas, and trade-offs in potential food production from land that was previously agricultural. This could precipitate negative effects on livelihoods and food security.

M) Afforestation of degraded non-forest land (using mixed, native species)
Aim: To provide increase carbon stock and associated benefits through afforestation of land that was degraded, but not previously forested

Potential contribution to achieving ICF objectives: Afforestation of degraded non-forest land using plantations of mixed, native species, is likely to deliver on multiple policy objectives, with reduced risk of negative impacts on ecosystems.

Potential positive impacts/synergies: This intervention is likely to provide biodiversity, carbon sequestration, and other regulating and provision services, but the actual contribution to each of these objectives depends strongly on the management goals and approaches. Increased biodiversity benefits can be expected relative to other afforestation interventions, and if the area was previously degraded, biodiversity may reach higher levels than the previous land use. Afforesting degraded land (such as degraded agricultural land or scrub land) can have significant positive benefits for carbon sequestration and storage, as above-ground, below-ground (roots) and soil carbon are all likely to be increased. This is also likely to have benefits for improvements regulating services such as soil erosion prevention and hydrological function including increased infiltration rates, storage capacity. Increased provisioning services can be expected, as these plantations are likely to deliver more timber, fuelwood, and potentially food and medicinal plants, depending on the previous land-use. These benefits depend very much on the management regime used. Biodiversity benefits depend on the species used and the natural vegetation cover of the area, and many of the regulating services of forests are dependent on the way in which the forest structure is managed. For example structure and composition of the understorey layer influences hydrological services, and has consequences for biodiversity. Biodiversity could also confer resilience to forest functions and increased ecosystem productivity of relevance to carbon storage (see section 1.1 on carbon stocks) and timber production (see section 1.3.1).

Potential negative impacts/trade-offs: There are likely to be trade-offs related to the opportunity cost of afforestation, the relative carbon and biodiversity values of the previous land-use, and the types of management regime chosen. For example, maximising biodiversity and carbon stocks of the site will reduce the potential for timber extraction and vice versa. There are also the costs of afforestation associated with establishment and maintenance. In addition, depending on previous land-use and how this approach is implemented, there may be risks such as land alienation or loss of access to natural resources for local people. This can depend on the criteria for site selection for afforestation, such as definitions of 'degraded land', as land considered degraded by one stakeholder may be used for grazing, fuelwood collection or shifting cultivation by others.

N) Restoration of degraded forest land (assisted natural regeneration)
Aim: To restore forest cover on degraded forest land, increasing carbon sequestration and providing other forest-related services

Potential contribution to achieving ICF objectives: Assisted natural regeneration (ANR) refers to interventions to speed up natural regeneration processes, including measures for encouraging seed dispersal, soil restoration, clearing competing vegetation, managing pests, and so on (Epple and Thorley, 2012).

Potential positive impacts/synergies: ANR can provide benefits for biodiversity conservation more rapidly than natural regeneration alone, and where biodiversity conservation is a priority, practices can be selected to maximise structural complexity and compositional diversity (Miles et al, 2010b). A meta-analysis of the effectiveness of restoration in restoring biodiversity and ecosystem services found that restoration increased provision of biodiversity and ecosystem services by 44 and 25%, respectively, across 89 studies, although values remain lower than in intact ecosystems; ecological restoration was found to be particularly effective in tropical areas (Rey Benayas et al., 2009). Under such approaches, forest biomass and tree species richness may begin to resemble those of mature forests after 30 to 40 years of secondary succession. Forest rehabilitation can significantly enhance carbon stocks in soil and vegetation, and re-establishing natural or near-natural forest through ANR generally leads to higher carbon stocks that establishing managed plantations (Epple and Thorley, 2012). Similarly, ANR approaches can have positive impacts on regulating ecosystem services such as water flows and quality at a faster rate than natural regeneration (although slower than plantations), and is likely to result in higher quality forest cover (Miles et al, 2010b). For provisioning services, species can also be selected to enhance the availability of NTFPs and medicinal plants, depending on the goals of the intervention. The relative benefits for biodiversity and ecosystem services depending on past land use and the distance to patches of undisturbed forest (as sources for plant and animal colonists) (Guariguata and Ostertag, 2001, and Lamb et al., 2005, in Kapos et al., 2012). ANR approaches can be adapted to prioritise provisioning services, such as NTFPs, food and fuelwood, although the impact of this on local livelihoods and wellbeing will depend on the selected species, local preferences and access to the forest. The enhanced biodiversity in ANR is also likely to confer a higher degree of resilience to change. Kozlowski (2002) notes that ANR often involves greater management intensity and often occurs in degraded sites where natural regeneration is not possible. Degraded sites may imply that accessibility and proximity to communities and markets may already be relatively high (Miles et al, 2010b).

Potential negative impacts/trade-offs: Forest restoration through planting native species and assisting natural regeneration can lead to increased water supply, as well as biodiversity benefits, although this can involve a trade-off in availability of NTFPs. It is also important to note the trade-off associated with natural regeneration, assisted and unassisted, regarding the investment in time and resources, and the uncertainty. The importance of securing resilient, resistant and dynamic ecosystems, under changing land-use conditions, can at times justify not attempting to recreate reference ecosystems. There may also be trade-offs in relative flows of provisioning ecosystem services if the reforestation project requires access restrictions to ensure successful regeneration of species. Similarly, if the land was previously used for agriculture, the reforestation project may trade-off food production, as well as medicinal plants and some NTFPs that prefer fallow or degraded areas (see section 1.3.2 on NTFPs). Depending on species, tree growth may reduce overall water flow, though better water quality can be expected relative to degraded land, but not established shrub or grassland which can be equally important for hydrological services.

O) Restoration of degraded forest land with little inputs

Aim: To allow natural regeneration processes to deliver biodiversity, carbon and ecosystem services benefits expected with secondary regenerated forest

Potential contribution to achieving ICF objectives: Restoration of degraded forest land can also be undertaken with little input except zoning (i.e. through fences to prevent herbivory) and occasional management.

Potential positive impacts/synergies. Restoration of forest land with little inputs is expected to contribute strongly to policy objectives, particularly biodiversity and carbon storage. Biodiversity and carbon storage benefits, in the long-term, are likely to more closely resemble those of natural forest than any type of afforestation project using plantation forestry. Flows of other regulating services and provisioning services are likely to be higher than the degraded forest land which the intervention is replacing because mature forest is likely to be beneficial for both soil protection and fertility, hydrological functions, and as sources of timber and fuelwood. Depending on the characteristics of the species, food and medicinal plants may be more plentiful in mature forest than degraded forest. The contribution of the regenerated forest to various regulating and provisioning ecosystem service functions will depend on the proximity to beneficiary communities, and the access afforded to local people to collect fuelwood, food and medicinal plants. Simultaneous contributions to biodiversity, carbon storage, and other regulating services objectives can be expected with some confidence. Furthermore, costs are reduced compared to other afforestation and reforestation approaches.

***Potential negative impacts/trade-offs**:* The resulting forest structure and composition, and the flows of ecosystem services and biodiversity associated with it, are likely to be more uncertain than ANR. Furthermore, the rate of regeneration is likely to be considerably slower than ANR, and the resulting contribution to policy objectives is likely to be achieved more slowly. As regeneration of species depends on natural propagation processes, the actual biodiversity and carbon stock levels reached will possibly be lower than ANR, the latter of which benefits from increased certainty of propagule supply and maintenance of the forest structure to ensure saplings have the chance to grow. Additionally, degraded sites can be important sources of food, fuelwood, and medicinal plants through a combination of increased accessibility, and utility values of disturbance-related species. Also, traded-off against the reduced costs of establishment are the increased time-scale for expected benefits to emerge, and the greater uncertainty as to the final biodiversity, carbon stocks, and regulating service levels that will be accomplished. Depending on previous land use, reforestation may reduce medicinal plants and some NTFPs that prefer fallow/ degraded areas and may reduce food production. If access is prevented to allow forest regeneration, there may be livelihood trade-offs for resource-users.

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Annex 1: Methods

In order to generate a list of literature appropriate for inclusion in this review, two peer-reviewed publication databases were searched: SciVerse's SCOPUS; and ISI's Web of Science, both of which cover natural and social sciences.

To search these online databases a search term is required which is a fusion of keywords describing the primary research question, and Boolean logic operators. The primary research question in this project was defined as "To what extent do tropical forest ecosystem services rely on biodiversity". To ensure that a reliable search term was created, the evolution of the term occurred in three main phases:

1. The initial search term was created by combining a list of keywords that the researchers, based on experience in working in this field, thought a relevant paper might contain, and keywords used in previous systematic literature searches with a similar focus.
2. In the second phase, the initial search term was refined. This was achieved by examining the papers that were captured using the search term. Keywords were then removed if they were found to capture large amounts of irrelevant papers; through reviewing the papers captured by the search, a number of keywords were added to ensure that as wide array of papers as possible was caught in the initial data gathering stages.
3. The final phase involved the development of various tiers within the search term in order to reduce the number of irrelevant papers being brought into the review. The exact details of the steps taken in the evolution of this search term are provided in Annex 2.

In Scopus, each journal is assigned one or more of 335 'subject areas', each of which falls under one of 27 major subject areas. It is these major subject areas which can be used to refine search results. The Scopus component of our search was therefore refined to the subject areas documented in Annex 2. ISI's Web of Science, by contrast, allocates individual articles to one or more of 156 'research areas' which can be included or excluded in order to refine the search. There are many overlaps between the Web of Science research areas and the Scopus subject areas but they are not directly comparable, therefore equivalent research areas were identified in Web of Science and were used to refine the data, with the aim to keep the refinement consistent across databases in order to achieve a comparable result. The exact research areas used to restrict the search are available on request.

The finalised search strings as shown below were then applied to both Scopus and Web of Science to search titles, abstracts and keywords. Due to syntactic differences in the way the search engines work, the search strings are not identical but search for the same terms and use the same Boolean logic.

Scopus Search Term:

TITLE-ABS-KEY ("ecosystem service" OR "ecosystem services" OR "ecological service" OR "ecological services" OR "natural capital" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "ecotourism" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder" OR "soil erosion" OR "soil degradation" OR "water quality" OR "flood" OR "flooding" OR "pollution" OR "Irrigation" OR "regulating service" OR "Regulating services" OR "provisioning service" OR "provisioning services")AND TITLE-ABS-KEY ("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR “community” OR “assemblage” OR “composition” OR “diversity” OR "ecological process" OR "ecological processes" OR "fauna" OR "flora" OR "vertebrate*" OR "invertebrate*" OR "bat" OR "snakes" OR "epiphyte" OR "liana" OR "vine" OR "shrub" OR "microorganism" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR “organism” OR “wetlands” OR “bamboo” OR “rattan”) AND TITLE-ABS-KEY (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment*” OR “resilience” OR "impact*" OR "affect*" OR "buffer*" OR "deliver*" OR "assess" OR "drive*" OR "improve*”)AND TITLE-ABS-KEY (“smallholder“ OR "subsistence" OR "livelihood" OR "livelihoods" OR "local" OR "community" OR "village" OR "household" OR "people*" OR "human*" OR “small scale farmer” OR “small scale farmers” OR “indigenous people” OR “forest dependent” OR “peasant*” OR “peasantry”) AND TITLE-ABS-KEY (“forest" OR “forests” OR “wood*” OR "deforestation" OR "forest degradation" OR “fragmentation”)

Web of Science Search Term:

TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR “natural capital” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "ecotourism" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder" OR "soil erosion" OR "soil degradation" OR "water quality" OR "flood" OR "flooding" OR "pollution" OR "Irrigation" OR "regulating service" OR "Regulating services" OR "provisioning service" OR "provisioning services")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR “community” OR “assemblage” OR “composition” OR “diversity” OR "ecological process" OR "ecological processes" OR "fauna" OR "flora" OR "vertebrate*" OR "invertebrate*" OR "bat" OR "snakes" OR "epiphyte" OR "liana" OR "vine" OR "shrub" OR "microorganism" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR “organism” OR “wetlands” OR “bamboo” OR “rattan”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment*” OR “resilience” OR "impact*" OR "affect*" OR "buffer*" OR "deliver*" OR "assess" OR "drive*" OR "improve*”)AND TS=(“smallholder“ OR "subsistence" OR "livelihood" OR "livelihoods" OR "local" OR "community" OR "village" OR "household" OR "people*" OR "human*" OR “small scale farmer” OR “small scale farmers” OR “indigenous people” OR “forest dependent” OR “peasant*” OR “peasantry”) AND TS=(“forest" OR “forests” OR “wood*” OR "deforestation" OR "forest degradation" OR “fragmentation”)

To increase the accuracy of the search, the keywords were divided into a number of ‘tiers’, with a tier defined as a block of keywords that is separated from the next tier by an ‘AND’ term. The use of tiers ensures that a paper is only captured if it includes at least one word from each tier, therefore by having each tier address a different part of the question, only papers that cover all the topics we are interested in are included. The table below describes the tiers used in this search.

Tier	Justification
Ecosystem service	This tier contained keywords describing ecosystem services.
Biodiversity	This tier contained a broad definition of biodiversity.
Linkage Term	This tier ensured that the paper had some language related to linkage, and therefore was more likely to describe a link between biodiversity and ecosystem services in some capacity.
Human	This tier was included to ensure that papers not directly talking about ecosystem services still included the impact that biodiversity had on people in some fashion and so could still provide useful evidence.
Forest	This tier was included to restrict the search to forests only, to save time.

After completing the two database searches, the results were combined and screened for duplicates using the bibliographic software Mendeley. After screening for duplicates a total of 16,322 papers remained, too many to fully review given the scope of this project. We therefore conducted a title and a subsequent abstract selection phase in order to eliminate papers that were clearly irrelevant and so reduce the number of papers for full review down to a more manageable number.

At the title stage, a paper was rejected if the title:

- Showed the paper was providing information on a OECD member,
- Did not mention component of biodiversity or a component of the ecosystem services as described in the search term.
- Implied that the paper did not refer to tropical forest.
- Was not in English.

At the abstract stage, a paper was rejected if the abstract:

- Showed the paper was providing information on a OECD member,
- Did not mention a component of biodiversity and a component of the ecosystem services as described in the search term.
- Implied that the paper did not refer to tropical forest.
- Was not in English.

Following the title selection stage, 2,956 papers remained. These papers were then assessed at the abstract stage using the above criteria, which resulted in a further 1,780 papers being rejected on the basis of lack of relevance, leaving a total of 1,176 papers to be obtained and subsequently reviewed. The total number of papers reviewed was further refined as papers lacking relevance to the topic were eliminated. The title and abstract selection phase of this project was undertaken by two members of the research team, and the list of papers further refined. To ensure consistency in the criteria used to accept and reject papers a kappa test was undertaken at both stages. The kappa test is a statistical test of agreement between two sources that is performed on a sample of 10percent of the total number of papers (up to 500).

The test compares the number of agreements that the two reviewers make (both either accept or reject a paper) compared to the number of papers which they disagree on (where one accepts and the other rejects). This is a proxy for whether they are using the same criteria to reject papers.

The kappa test for the title level search was: 0.75 – which is classified as being an excellent level of agreement between parties. The kappa test for the abstract level search was: 0.40 – classified as fair to good agreement, but indicating that the reviewers were accepting and rejecting on different criteria. Therefore for consistency the reviewers discussed the criteria for the abstract level search again. After this discussion, they reviewed a sample of abstracts and redid the kappa test. This time with the result was 0.65, which is classified as good.

In order to split the papers and systematically review them for their content, each of these papers was tagged with an ecosystem classification, using the Millennium Ecosystem Assessment (MEA) classification of provisioning, supporting, regulating and cultural services, as well as a number of further tags listed in Annex 2 to facilitate the easy splitting of papers between reviewers. Papers were reviewed through each reviewer answering the following questions about each paper:

Question:	**Answer type:**
Basic Information:	
Method used:	Experiment; observation; interviews; model
Forest type:	Free text
Biodiversity-ecosystem service linkage:	
Ecosystem service classification	Provisioning, regulating, supporting, cultural
Sub category	Free text
Is a relationship between biodiversity and this ecosystem service found?	Yes, No
Is the relationship between biodiversity positive or negative?	Positive, negative
A description of the linkage:	Free text
Conservation status and action:	
Does the paper describe a conservation intervention?	Yes, No
Is there any evidence that intervention affects the described ecosystem service?	Yes, No
Are rare or threatened species mentioned?	Yes, No
Is any relationship between these rare/ threatened species and the aforementioned	Yes, No

ecosystem services mentioned?	
Policy/management implications:	
Does the paper on the basis of its findings offer any recommendations on how to manage biodiversity to promote ecosystem services?	Yes, No
If yes, what?	Free Text

Annex 2: Evolution of search term

Web of Science – Search term for points 1 & 2.

Search Term	Number of records	Comments
TS=(ecosystem service OR ecosystem services) AND TS=(biodiversity)	2,978	Basic search, split into two tiers, ecosystem service and biodiversity. High number of irrelevant studies.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity)	3,114	Added some variations on biodiversity.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity)	3,776	Added some more general terms used.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources)	4,231	Added some more general terms used.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry)	5,563	Added some biodiversity descriptors to try to capture the species element of the CBD definition of biodiversity.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR species OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry)	5,785	Added species.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-	6,631	Added biomes.

diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR species OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry OR forest* OR dryland* OR ocean* OR savanna* OR mountain* OR mangrove* OR coastal OR grassland* OR marine OR freshwater OR taiga OR shrubland* OR woodland* OR tundra OR desert)		
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR species OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry OR forest* OR dryland* OR ocean* OR savanna* OR mountain* OR mangrove* OR coastal OR grassland* OR marine OR freshwater OR taiga OR shrubland* OR woodland* OR tundra OR desert OR ntfp OR non timber forest product OR non-timber forest product OR nontimber forest product OR non timber forest products OR non-timber forest products OR nontimber forest products OR nwfp OR non wood forest product OR non-wood forest product OR non wood forest products OR non-wood forest products OR timber OR charcoal OR fuelwood OR firewood OR wood)	7,870	Added non timber forest product and its variants.
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR species OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry OR ecosystem* OR ecological system OR habitat* OR forest* OR dryland* OR ocean* OR savanna* OR mountain* OR mangrove* OR coastal OR grassland* OR marine OR freshwater OR taiga OR shrubland* OR woodland* OR tundra OR desert OR ntfp OR non timber forest product OR non-timber forest product OR nontimber forest product OR non timber forest products OR	7,870	Added ecosystem, ecological system and habitat.

non-timber forest products OR nontimber forest products OR nwfp OR non wood forest product OR non-wood forest product OR non wood forest products OR non-wood forest products OR timber OR charcoal OR fuelwood OR firewood OR wood)		
TS=(ecosystem service OR ecosystem services) AND TS=(Biodiversity OR biodiversity OR biological diversity OR bio-diversity OR nature OR wildlife OR genetic diversity OR natural resources OR natural resources OR species OR mammal* OR bird* OR plant* OR reptile* OR tiger* OR elephant* OR great ape OR great-ape OR great apes OR great-apes OR gorilla OR chimpanzee OR duiker* OR lion* OR primate* OR amphibian* OR insect* OR tree* OR animal* OR fungus* OR fungi OR mushroom* OR fruit* OR vegetable* OR bushmeat OR fish OR *livestock OR cattle OR goat* OR sheep OR chicken OR poultry OR ecosystem* OR ecological system OR habitat* OR forest* OR dryland* OR ocean* OR savanna* OR mountain* OR mangrove* OR coastal OR grassland* OR marine OR freshwater OR taiga OR shrubland* OR woodland* OR tundra OR desert OR ntfp OR non timber forest product OR non-timber forest product OR nontimber forest product OR non timber forest products OR non-timber forest products OR nontimber forest products OR nwfp OR non wood forest product OR non-wood forest product OR non wood forest products OR non-wood forest products OR timber OR charcoal OR fuelwood OR firewood OR wood OR medicinal plant OR medicinal plants)	7,870	Added medincinal plant, medincinal plants.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR	10,511	Added food security, safety net, ethnomedicine, ethnoveterinary, livelihood and “” around all terms to ensure that that term exactly is searched for.

"charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants")		
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood") AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants")	5,515	Added new tier with ecosystem service, ecosystem services to ensure that all paper make some reference to ecosystem services.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood") AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non	1,454	Added a new tier with support, depend, facilitate, provides in an attempt to get to the papers discussing how biodiversity supports the provisioning of ecosystem services.

wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants") AND TS = ("support" OR "depend" OR "facilitate" OR "provides")		
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "provision*") AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants") AND TS = ("support" OR "depend" OR "facilitate" OR "provides")	1,454	Added wellbeing and provision to the ecosystem service description tier
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "water cycling" OR "water filtration" OR "water purification" OR "protection") AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock"	3,269	Added emergency, provision, flood protection, provision, storm protection, landslides, carbon sequestration, carbon storage, water cycling, water filtration, water purification and protection to ecosystem service description tier.

OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants") AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*”)		Changed provides to provide* 4h tier.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*” OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection”) AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants") AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying”)	3,402	Added carbon and water cycling to ecosystem description tier.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR	4,158	Community, assemblage,

“wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection”) AND TS = ("ecosystem service" OR "ecosystem services") AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)		composition, diversity added to biodiversity description. Value, valuation and resilience added to forth tier.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection”) AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR	165,069	Removed second tier which had “ecosystem services” in it.

"cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "dryland*" OR "ocean*" OR "savanna*" OR "mountain*" OR "mangrove*" OR "coastal" OR "grassland*" OR "marine" OR "freshwater" OR "taiga" OR "shrubland*" OR "woodland*" OR "tundra" OR "desert" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)		
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection”) AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)	159,220	Removed unnecessary biomes.

		Decided to split the search into two searches a global and local search focusing on different ecosystem services.
Local Search		
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection”)AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "wood" OR "medicinal plant" OR "medicinal plants" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)	71,239	Limited the ecosystem services tier to the local ecosystem services.
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest	170,060	Moved NTFP related search terms, medicinal plants, and fuelwood related terms from biodiversity tier to ecosystem tier.

products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment "OR "resilience")		
TS=("ecosystem service" OR "ecosystem services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "carbon" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater"	211,285	Moved livestock, cattle, poultry to the ecosystem service tier.

OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment "OR "resilience")		
TS=("ecosystem service" OR "ecosystem services" OR "ecological service" OR "ecological services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "carbon" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment "OR "resilience")	221,260	Added variation on ecosystem services name to account for changes in language.
TS=("ecosystem service" OR "ecosystem services" OR "ecological service" OR "ecological services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "carbon" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest	221,260	Added cultural ecosystem services and indirect uses such as tourism.

product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "tiger*" OR "elephant*" OR "great ape" OR "great-ape" OR "great apes" OR "great-apes" OR "gorilla" OR "chimpanzee" OR "duiker*" OR "lion*" OR "primate*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment "OR "resilience")		
TS=("ecosystem service" OR "ecosystem services" OR "ecological service" OR "ecological services" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "carbon" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR "	220,485	Removed primates, great apes and variants, as well as other specific animals.

wood" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)		
TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)	225,223	Added pollination and animal fodder to search term.
TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR	39,342	Looked at the search results and realised that a large amount of the literature was not relevant as it didn’t have a human component tier to ensure that the search results included biodiversity, ecosystem services and local scale

"charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)AND TS=(“smallholder“ OR "subsistence" OR "livelihood" OR "livelihoods" OR "local" OR "community" OR "village" OR "household")		people. Therefore added a tier including terms to ensure the papers were of a local scale and relevant to people.
TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR “natural capital” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*” OR " wood" OR “community” OR “assemblage” OR “composition” OR	6,038	Added a tier to ensure that all results were relevant to forest ecosystems in line with the aim of the study. Also added “Natural capital to biodiversity description”

“diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)AND TS=(“smallholder“ OR "subsistence" OR "livelihood" OR "livelihoods" OR "local" OR "community" OR "village" OR "household") AND TS=(“forest" OR “forests” OR “wood*”)		
TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR “natural capital” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water cycling” OR “water filtration” OR “water purification” OR “water cycling” OR “protection” OR "ntfp" OR "non timber forest product" OR "non-timber forest product" OR "nontimber forest product" OR "non timber forest products" OR "non-timber forest products" OR "nontimber forest products" OR "nwfp" OR "non wood forest product" OR "non-wood forest product" OR "non wood forest products" OR "non-wood forest products" OR "timber" OR "charcoal" OR "fuelwood" OR "firewood" OR "medicinal plant" OR "medicinal plants" OR "*livestock" OR "cattle" OR "goat*" OR "sheep" OR "chicken" OR "poultry" OR "ecotourism" OR "empowerment" OR "vulnerability" OR "energy security" OR "Pollination" OR "Animal fodder")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*” OR " wood" OR “community” OR “assemblage” OR “composition” OR “diversity”) AND TS = (“support*” OR “depend*” OR “facilitate*” OR “provide*” OR “basis” OR “underlying” OR “value” OR “valuation” OR “assessment ”OR “resilience”)AND TS=(“smallholder“ OR "subsistence" OR "livelihood" OR "livelihoods" OR "local" OR "community" OR "village" OR "household") AND TS=(“forest" OR “forests” OR “wood*”)	6,038	**Final Version of Local Search Term**
Global Level Search		
TS=("ecosystem service" OR "ecosystem services" OR “ecological service” OR “ecological services” OR “natural capital” OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR “wellbeing” OR “emergency” OR “provision*" OR “flood protection” OR “storm protection” OR “landslides” OR “carbon sequestration” OR “carbon storage” OR “carbon” OR “water	5,441	Removed the local ecosystem services and replaced with more regional/global.

cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ecotourism" OR energy security" OR "Pollination" OR "Animal fodder" OR "nutrient cycling" OR "soil erosion" OR "soil organic matter" OR water retention")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment" OR "resilience")AND TS=("global" OR "regional" OR "national" OR "worldwide") AND TS=("forest" OR "forests" OR "wood*")		In addition added nutrient cycling, soil erosion, soil organic matter water retention Also changed the human scale tier to global keywords to reduce the overlap of the searches.
TS=("ecosystem service" OR "ecosystem services" OR "ecological service" OR "ecological services" OR "natural capital" OR "food security" OR "safety net" OR "ethnomedicine" OR "livelihood" OR "wellbeing" OR "emergency" OR "provision*" OR "flood protection" OR "storm protection" OR "landslides" OR "carbon sequestration" OR "carbon storage" OR "carbon" OR "water cycling" OR "water filtration" OR "water purification" OR "water cycling" OR "protection" OR "ecotourism" OR energy security" OR "Pollination" OR "Animal fodder" OR "nutrient cycling" OR "soil erosion" OR "soil organic matter" OR water retention")AND TS=("Biodiversity" OR "biodiversity" OR "biological diversity" OR "bio-diversity" OR "nature" OR "wildlife" OR "genetic diversity" OR "natural resources" OR "natural resources" OR "species" OR "mammal*" OR "bird*" OR "plant*" OR "reptile*" OR "amphibian*" OR "insect*" OR "tree*" OR "animal*" OR "fungus*" OR "fungi" OR "mushroom*" OR "fruit*" OR "vegetable*" OR "bushmeat" OR "fish" OR "ecosystem*" OR "ecological system" OR "habitat*" OR "forest*" OR "mountain*" OR "mangrove*" OR "coastal" OR "freshwater" OR "shrubland*" OR "woodland*" OR " wood" OR "community" OR "assemblage" OR "composition" OR "diversity") AND TS = ("support*" OR "depend*" OR "facilitate*" OR "provide*" OR "basis" OR "underlying" OR "value" OR "valuation" OR "assessment" OR "resilience")AND TS=("global" OR "regional" OR "national" OR "worldwide") AND TS=("forest" OR "forests" OR "wood*")	5,441	**Final Version of Global Search Term**
Combined total (assuming no overlap of titles)	**11,479**	

Annex 3: Trade-offs and synergies for biodiversity, carbon storage and other ecosystem services related to interventions in tropical forests

Please note that a) the list of interventions is not exhaustive; and b) the impacts and interactions significantly depend on the methods used for interventions and the previous land use.

Intervention	**Potential impacts on ICF objectives** (for each intervention type, including positive (+), negative (-) and neutral (0) impacts on carbon storage, biodiversity and human wellbeing and livelihoods through impacts on ecosystem services (ES). A combination of impacts (e.g. +/-) indicates that these will depend significantly on the methods and previous land use related to the intervention).							**Synergies and trade-offs** (for each intervention type, there are potential interactions between the different impacts; multiple positive impacts provide potential for achieving synergies and negative impacts highlight potential for trade-offs).	
	Biodiver-sity	**Carbon storage**	**Other regul-ating ES**	**Timber**	**Fuel-wood**	**Food**	**Medic-inal products**	**Positive**	**Negative**
Agricultural intensification (high energy and chemicals input)	+/-	+/-	+/-	o	+/-	+/-	o/-	Likely increase in yields and food production may spare land elsewhere and reduce losses in standing forests (or conversion of other ecosystems), with benefits for carbon storage, biodiversity and ES. Improved food production and incomes for farm owners	Often significantly reduced biodiversity, carbon storage & other ES within intensive landscapes (e.g. risk of reducing pollination, which is important for food production). Risk of making agriculture more profitable and thus increasing demand for land. Risk of land alienation for smallholders. Potential impacts of chemicals on the surrounding environment/ communities.

	Biodiver-sity	Carbon storage	Other regul-ating ES	Timber	Fuel-wood	Food	Medic-inal products	Positive	Negative
Improvements to conventional/traditional agriculture	+/-	+/-	+/-	+/o	+/o	+/-	+/o	Improved local livelihoods through increased yields/ efficiency/sustainability. Potential financial premium from organic/conservation may increase incomes. If increased income achieved, may spare land elsewhere as earn more from same/smaller plot (as with intensification). Potentially beneficial for biodiversity, soil, water, carbon storage and other ES within agricultural land/on-site, compared to other farming methods.	Increased incomes may not be achieved due to reduced crop yields in the short term (compared to intense agriculture, especially during conversion period). Risk of increasing incomes increasing demand for agricultural land (e.g. to expand organic farming). And depending on traditional methods being advanced, risk of encouraging unsustainable practices (e.g. burning). Potentially demanding in terms of cost and time.
Improved fire management (where existing fire risk/damage)	+/-	+	+	+/-	+/-	+/-	o	Improved carbon storage, biodiversity, provisioning and regulating ES, and human wellbeing by reducing uncontrolled fires.	May reduce land availability in short term for shifting cultivation or plantation agriculture. If fires are reduced within fire adapted ecosystems, it can negatively affect biodiversity (potentially incl. NTFPs spp.).

Conversion of agricultural land to agroforestry	+/o	+	+	+	+	+/-	+	Depending on management, improved carbon storage, biodiversity, provisioning and regulating ES. Potentially increased food security and/or income security (via diversification) for smallholders.	Extensive agroforestry systems which maximise profitability are likely to have lower biodiversity, carbon storage and other ES benefits (although may still exceed that of intensive agriculture). Negative impact on food production/security may arise, depending on the specific conversion undertaken/ crops being produced.
Maintaining natural forest through establishing or reinforcing Protected Areas (i.e. IUCN class I, II)	+	+	+	-	-	+/-	+/-	If areas would otherwise be under threat from degradation, PA likely to protect carbon stocks, biodiversity and regulating services (degree of benefits depends on spatial congruence of these ES and location of PA relative to beneficiaries). May protect source population for provisioning services (e.g. mangrove PA can be a hatchery for fisheries, and so increase fish catches outside PA)	May affect supply of provisioning ES if restrictions are placed on local populations that previously relied on extraction within the PA; If restrictions placed on extraction it may also increase pressure on other ecosystems (displacement of extractive pressure).

Community forestry	+/- +/- +/- +/- +/- +/- +/-	Depending on management, can meet both conservation and livelihoods objectives, with benefits for provisioning and regulating ES. If community management increases legitimacy and decreases conflict, benefits to biodiversity can exceed those of poorly managed PAs.	Extractive use is likely to have some impact on carbon storage and biodiversity. If community requirements for provisioning ES are high, it can be hard to maintain the sustainability of extraction. Requires establishing sustainable management practices which can be demanding in terms of cost and time
Reduced impact logging (relative to conventional logging)	+/- +/- +/- +/- +/- +/- +/-	Depending on full implementation, improved ES by reducing damage to forest ecosystems, impacts on biodiversity (incl. from hunting, roads). Certification may bring price premium/access to markets.	Extractive use is likely to have some impact on carbon storage and biodiversity (compared to no disturbance). Could increase costs relative to conventional logging. Levels of provisioning ES to communities depends on access.
Sustainable harvesting and/or alternative production of NTFPs	+/- +/- + o/+ o/+ +/- +/-	Benefits for carbon storage, biodiversity and income/food security from NTFPs, and sustainability of these ES. Reduced degradation of forests	Extractive use is likely to have some impact on carbon storage and biodiversity, depending on the management practise in place. May be more costly compared

								may have positive impact on timber/fuelwood provision. Potential benefits associated with increased social harmony/rights of local people.	to unregulated extraction and reduce uptake from poor communities dependent on NTFPs. Increased profits may promote over-exploitation.
Fuel substitution/ efficiency	+	+	+	+	o/+	+	o/+	Benefits for carbon storage, biodiversity, provisioning and other regulating ES associated with reduced pressure on standing forests. Health benefits and pollution reduction.	Costs of improved cookstoves/ fuel substitution.
Hunting regulation (relative to uncontrolled wildlife hunting)	+	+/o	o/+	o/+	o/+	o/+	o/+	Can improve sustainability of bushmeat harvest thus ensure longer-term supply of important food source. Hunting licenses may offer funding stream. May reduce illegal exploitation and thus benefit provision of timber, fuelwoodand other provisioning ES over longer term May reduce forest degradation associated with loss of certain spp from forest.	Depending on species and whether substitution/ alternatives promoted, may reduce overall meat supply. Enforcement costs and potentially lack of uptake among communities if affects important food/income source.

Monoculture plantations (timber/tree crops of non native species on non-forest land)	-	+/-	+/-	+	+/-	-	-	Depending on management and previous land-use, may lead to improved carbon storage. For e.g., long return timber harvests can sequester and store carbon for long periods. Likely to increase timber supply, and potentially fuelwood supply, and so may reduce pressure to convert natural forests. Potential for short-term restoration of regulating ES (faster than other interventions).	Monoculture plantations are generally low in biodiversity and are likely to have significant negative impacts on biodiversity and ES if land converted was previously a biodiverse intact ecosystem. Overall functions likely limited by management methods; if replacing agricultural land/secondary forest, can affect provisioning ES (unless implemented in socially responsible way).
Mixed plantations (timber/tree crops of mixed, native species on non-forest land)	+/-	+/-	+/-	+/-	+/-	+/-	+/-	Timber yields could approximate those of monoculture if there's complementarity and niche differentiation between species. Timber supply/fuelwood supply from plantation may reduce pressure on natural forests. Mixed plantations have higher biodiversity than monocultures and can conserve some species. May increase some provisioning ES (depending on management and access)	Impact on biodiversity depends on previous land use. May increase costs compared to single species plantation. Many NTFPs are found in fallow/ degraded areas (esp. medicinal plants). Potential trade-off with livelihoods/food security (unless implemented in socially responsible way). Regulating ES provision depends on management of

								May be more resilient to disturbances and provide more regulating ES, compared to monocultures.	understorey and soil.
Afforestation of degraded non-forest land (using mixed, native species)	+/-	+	+/-	+/-	+/-	+/-	+/-	Likely to have significant benefits for carbon storage, biodiversity and ES, depending on spp. used. Depending on management regime, may provide provisioning ES. Depending on management, soil fertility, protection and flood prevention ES benefits likely to be substantial.	Impact on biodiversity will depend on the species used and the natural vegetation cover of the area. Depending on previous land use may reduce food production. As well as medicinal plants and some NTFPs (that prefer fallow/ degraded areas). Depending on species, tree growth may reduce overall water flow (though likely to be better quality compared to runoff from degraded land, not necessarily compared to established shrub or grassland).
Restoration of degraded forest land (using enrichment planting with mixed native spp.)	+	+	+/-	+/-	+/-	+/-	+/-	Very likely to increase carbon stocks. Very likely to increase biodiversity. May increase provisioning ES including NTFPs, depending on spp. used and access. Likely to improve regulatory ES.	Level of enhancement of carbon stocks will partly depend on previous land cover May reduce medicinal plants and some NTFPs (that prefer fallow/degraded areas). Depending on previous land use may reduce food production.

			Depending on species, tree growth may reduce overall water flow (though likely to be better quality; not necessarily compared to established shrub or grassland).
Restoration of degraded forest land (natural regeneration, i.e. with little input except zoning/ occasional management)	+ + + - + + +	Very likely to increase carbon stocks. Very likely to increase biodiversity. May provide more provisioning ES including NTFPs, depending on spp. used and access. Likely to improve regulatory ES.	Level of enhancement of carbon stocks will partly depend on previous land cover. May reduce medicinal plants and some NTFPs (that prefer fallow/ degraded areas). Depending on previous land use may reduce food production. Depending on species, tree growth may reduce overall water flow (though likely to be better quality; not necessarily compared to established shrub or grassland).