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Synergies between climate change, biodiversity, ecosystem function and services, indirect drivers of change and human well-being in forests

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Abstract Climate change is having impacts on the biodiversity and structure of many ecosystems. In this chapter, we focus on its impacts on forests. We will focus on how the potential climate change impacts on forest biodiversity and structure will have a reflection on the ecosystem services provided by forests, and therefore on the capacity of these ecosystems to support the Sustainable Development Goals set by the United Nations. The chapter will be organized in three sections, considering boreal, temperate and tropical forests along each section. The first section will deal with the synergies or interactions between climate change, biodiversity and ecosystem function with emphasis not only on plants but also on fungi, animals and prokaryotes. Synergies between climate change and ecosystem services will be described and analyzed in the second section. To better link the first two sections, we will explore the relationships between ecosystem function, species traits and ecosystem services. Finally, case

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studies for boreal, Mediterranean and tropical forests will be presented, emphasizing the synergies between the above factors, the indirect drivers of change (demographic, economic, sociopolitical, science and technology, culture and religion) and human well-being (basic materials for a good life, health, good social relations, freedom of choice and actions) in forests.

1. Introduction

The terrestrial and aquatic ecosystems of the Earth are connected by cycles of water, carbon and nutrients controlled by the dynamics of climate, which is powered by solar energy. The interactions between these cycles and climate are modulated in part by forests both at the local and global scales. These interactions result in various synergies, as we shall see in this chapter, that generate complexity and dynamic stability which can make difficult to predict dynamics of ecosystem attributes and services (Perry et al. 2008). Forests cover about 30% of world's land area (Shvidenko et al. 2005). Through their low surface albedo (e.g., they warmer climate during snow season relative to treeless area), high carbon storage capacity (~45% of terrestrial carbon), high CO_2 uptake (~50% of terrestrial net primary production), and by changing their evapotranspiration rates which cool the climate and affect rain patterns, forests can influence climate and the hydrologic cycle (Bonan 2008). Forests also can regulate streamflow and influence water quality (Perry et al 2008). Additionally, they provide provisioning (e.g., water and timber), regulating (e.g., carbon sequestration), supporting (e.g., biogeochemical cycling) and cultural (e.g., recreational) services to human kind (MEA 2005).

The importance of the above functional attributes and ecosystem services generally vary depending on the type of forest. Among these, three forest types predominate on the Earth's continents. Thus, boreal, temperate and tropical forests represented 26.5, 16.1 and 57.2% of total forest cover in 2010, respectively (Hansen et al. 2013). According to Bonan (2008), boreal forests have moderate climate control through moderate carbon storage, weak evaporative cooling and strong albedo decrease (i.e., sun absorption).; temperate forests have moderate climate control through strong carbon storage, moderate evaporative cooling and moderate albedo decrease; and tropical forests have strong climate control through strong carbon storage, strong evaporative cooling and moderate albedo decrease. Although boreal forests have very low human population density and a low number of tree species, more than 33% of the lumber and 25% of the paper of the global export market originate from this biome (Gauthier et al. 2015). Human boreal communities benefit from ecosystem services provided by the forest for fishing, hunting, leisure, spiritual activities and economic opportunities. In the temperate zone, tree biodiversity is intermediate and human npopulation density is generally high and concentrates in rural areas and especially in cities. Forests close to these population centers are often utilized intensively as a source of recreation-related, non-forestry activities (e.g., hunting, fishing and mushroom picking). However, they constitute a source of industrial roundwood of the same magnitude to that of boreal forests (FAO 1999). Tropical forests hold the highest biodiversity on Earth, which provides a wide range of ecosystem services on which 1.2-1.5 billion people benefit directly (Lewis et al. 2015); from this, almost 820 million people live in forests, savannas and surroundings, and 250 million of them are under the thresholds of extreme poverty (FAO 2018).

During the period 2000-2012, the tropics were the only domain to exhibit a significant trend in annual forest loss due to the prevalence of deforestation dynamics. Boreal forest loss followed that in tropical forests due largely to fire and forestry. Temperate forests, however, showed relatively low losses mainly due to fire, logging and disease (Hansen et al. 2013). Indeed, temperate and boreal forest cover has stabilized and even increased in the last decades, but their quality is still threatened by air pollution, fire, pest and disease outbreaks, continued fragmentation and inadequate management (Shvidenko et al. 2005). In general, it appears that these patterns will be maintained or accentuated in the near future (e.g., Seidl et al. 2011) and pose a real threat not only to forest health and the delivery of ecosystem services, but also to the overall functioning of the global system (Prăvălie 2018). Furthermore, climate change threatens forests in all biomes, both directly and through synergies with natural and other anthropogenic disturbances.

In this chapter, we will focus on how the ongoing and potential climate change impacts on forest biodiversity and function will have a reflection on the ecosystem services provided by forests, and therefore on their capacity to support the Sustainable Developing Goals set by the United Nations. First, we will deal with the synergies or interactions between climate change, biodiversity and ecosystem function putting emphasis not only on plants but also on fungi, animals and prokaryotes. Then, synergies between climate change and ecosystem services will be described and discussed. Next, to better link the previous two sections we will explore the relationships between ecosystem function, species traits and ecosystem services. Finally, case studies for boreal, temperate (in its Mediterranean version) and tropical forests will be presented, emphasizing the synergies between the above factors, the indirect drivers of change (demographic, economic, sociopolitical, science and technology, culture and religion) and human well-being (basic materials for a good life, health, good social relations, freedom of choice and actions) in forests.

2. Synergies between climate change, biodiversity and ecosystem function

2.1 Climate change impacts on forest biodiversity

Earth’s forest biomes are facing rapid and increasingly profound stress associated with climate change. Global trends attributable to climate change include latitudinal and elevational range shifts, phenological advances in growth or reproduction, and changes in disturbance patterns (i.e., tree pest and diseases, fire and drought) resulting in changes in community structure and function and delivery of ecosystem services.

Distribution of species has recently shifted to higher latitudes at a median rate of 16.9 kilometers per decade and to higher elevations at a median rate of 11.0 meters per decade (Chen et al. 2011). Northern boreal forests are migrating northward into tundra while southern boreal forests shift to shrub lands or grasslands in response to global warming (Allen and Breshears 1998). Likewise, tropical species are increasingly incorporated into temperate communities affecting food webs and resulting in new species interactions (Scheffers et al. 2016). For example, populations of insect defoliators and bark beetles are expanding to northern latitudes and higher altitudes in response to climate change affecting novel host species (Pureswaran et al. 2018). The rates of diversity turnover for microbes across temperature gradients from tropical to boreal forests are substantially lower (i.e., 2-8 times lower) than those recorded for trees and animals, suggesting that the diversity of plant, animal and soil microbial communities show differential responses to climate change (Zhou et al. 2015), and that latitudinal shifts of microbes might be proceeding at lower rates. However, a warming threshold might be reached in how trees interact with fungi, so the existing forest transition from low-latitude arbuscular mycorrhizal through N-fixer to high latitude ectomycorrhizal forests (Steidinger et al. 2019) can be disrupted resulting in different types of ecosystems. Elevational range shifts caused by climate warming have been described in boreal, temperate and tropical forests. For instance, bird distributions (Kischman and van Heuren 2017) and tree lines (Cazzola et al. 2019) have shifted upward 83 m in 40 years and 150 m in 52 years, respectively, in two boreal forests. Similarly, summer drought increase has caused a 70 m upward shift of European beech in a 50-year period through progressive replacement of cold-temperate ecosystem by Mediterranean ecosystems (Peñuelas and Boada 2003). Likewise, upslope shifts of moths (i.e., 67 m in 42 year) and birds distributions (i.e., 95-152 m in 50 years) have been found in tropical mountains (Chen et al. 2009, Freeman and Class Freeman 2014). Although higher latitudinal areas are undergoing the largest increases in temperature (Diffenbaugh and Field 2013), at least for birds, tropical montane species are responding more strongly to climate change than temperate-zone species, apparently due to higher sensitivity to warmer temperatures of tropical species (Freeman and Class Freeman 2014). The impacts of species redistribution will affect at least 11 of the United Nation´s Sustainable development goals (e.g., SDG3 Good Health and Well Being). However, current global goals, policies and international agreements do not sufficiently take into account species range shifts in their formulation or targets (Pecl et al. 2017).

Longer growing seasons of plants are occurring predominantly via warming of the coldest days in late winter and early spring (Cleland et al. 2007), potentially contributing to an increase in carbon sequestration. Forest vegetation phenology changed dramatically between 1981 and 2012 especially in the boreal and northern temperate regions (Buitenwerf et al. 2015). These changes appeared to be regulated by temperature and photoperiod cues (Del Pierre et al. 2016), while tropical ecosystems appear to be more influenced by precipitation variability (Cleland et al. 2007). Differential phenological shifts can cause mismatches between plant and pollinator population and lead to the extinctions of plant and pollinator species (Lavergne et al. 2010), with expected cascading effects on community structure and function.

Evidence of climate change effects on pest and diseases in boreal (Boyd et al. 2013) and temperate forests (Millard and Stevenson 2015) is mounting. This is relevant because tree pest and diseases can affect the ability of forests to sequester and store carbon, reduce flood risk and purify water, damaging also provisioning and cultural services (Boyd et al. 2013). Global climate models predict an increase in fire frequency and intensity under climate change (Moritz et al. 2012). Although in some parts of the world like the western USA forests, this is already a fact and it has resulted in reductions in forest productivity, greater tree mortality, and increased opportunities for colonization by plants (Grimm et al. 2013). These anticipated and ongoing changes in fire patterns along with the fact that bacteria appear to be more resistant to fire than fungi, and both of them less resistant than mesofauna, translates into important changes in ecosystem structure and function. The impacts are further exacerbated by the lack of resilience to fire of these biological communities (Pressler at al. 2018). In temperate forests, interactions between increasing temperatures resulting in “hotter droughts”, native insects and pathogens, and uncharacteristically severe wild fires are resulting in unprecedented forest mortality (Millar and Stephenson 2015). In tropical forests, synergistic effects between fragmented forests and climate change are provoking important changes in plant and animals species composition (Brooks et al., 2008, Laurance et al., 2014). Disturbance recovery time of leaf area and transpiration (i.e., water regulation services) is decades, while carbon storage functions take decades to centuries and biodiversity, coarse woody debris and nutrient mineralization can take even longer (Blanco 2012, Trumbore et al. 2015). These die-offs have an impact on people with a reduction in timber supplies and carbon sequestration and changes in water quality (Scheffers et al. 2016).

2.2 Climate Change Impacts on Forest Ecosystem Function

Climate change is being caused by an artificial increase in greenhouse gases in the atmosphere. Among those gasses, carbon dioxide (CO_2) is the most important producing greenhouse effect.

CO_2 is also growth-limiting factor for plants as they use it to create carboxylates during the photosynthesis. Increasing levels of atmospheric CO_2 concentration (*Ca*) enhance the rate of carboxylation by the photosynthetic enzyme system and reduce photorespiration (Norby et al. 1999). Likewise, rising *Ca* will decrease stomatal conductance, which results in an increase of water-use efficiency (WUE), that is, the ratio of the carbon gain to water loss (Fig. 1a) (Farquhar et al. 1989, Körner 2000). In addition, soil moisture savings due to reduced transpiration and changes in leaf area index have been associated with increasing *Ca* (Fatichi et al. 2016). The combined direct and indirect effects have been commonly referred as CO_2 fertilization (Holden et al. 2013). Consequently, an improvement of forest productivity is expected (Gedalof and Berg 2010). However, although some studies reported positive growth responses (e.g. LaMarche et al. 1984, Martínez-Vilalta et al. 2008), neutral and negative responses have been also found (e.g. Peñuelas et al. 2011, Silva and Anand 2013, Lévesque et al. 2014, Camarero et al. 2015). Such inconclusive results reveal that there are other factors controlling the growth-rising *Ca* relationship.

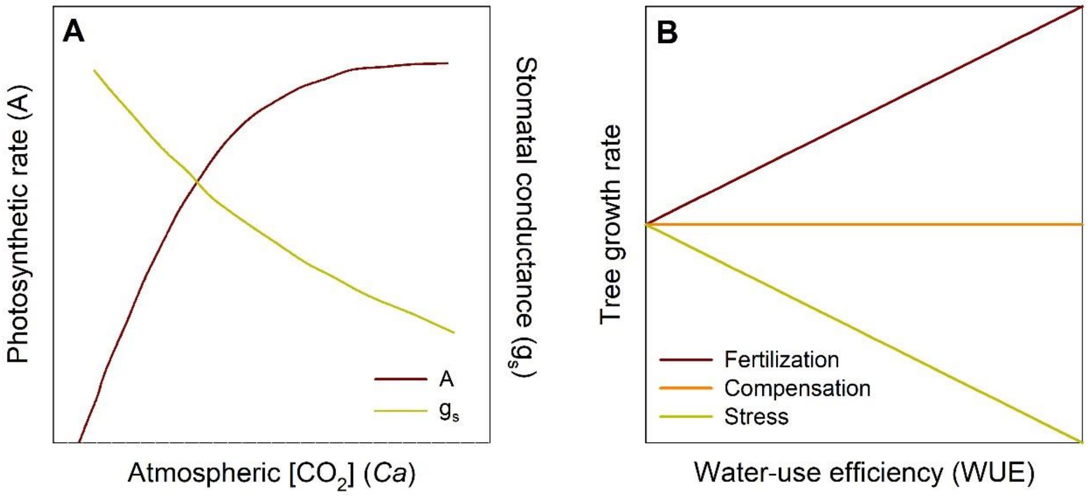

Fig. 1. (**a**) Relationship among photosynthetic rate (A), stomatal conductance (g_s) and atmospheric CO_2 concentration (*Ca*) for unstressed trees (own elaboration based on Regehr et al. 1975); (b) Expected relationships between water-use efficiency (WUE) and tree growth (own elaboration based Silva and Anand 2013). When increased WUE, resulting from rising *Ca* and/or water stress can override physiological response to stress, CO_2 fertilization effect of growth is expected (*Fertilization*). Conversely, if water stress is too strong, a negative growth-WUE would occur (*Stress*). No change is expected when CO_2 stimulation compensates for stress (*Compensation*).

Climatic conditions play an important role in modulating forest responses to rising *Ca*. Warming likely enhance tree growth through the positive influence on xylogenesis activity (Rossi et al. 2008), or the lengthening of growing season (Poulter et al. 2013). Despite the combined effect of increased temperature and improved WUE, global growth response patterns in relation to rising *Ca* have been proposed to be dependent on water stress (Fig. 1b) (Silva and Anand 2013). In regions where water is not a limiting factor (i.e. high latitude or altitude), growth stimulation has been observed (Salzer et al. 2009, Silva et al. 2010). The growth–WUE relationship becomes progressively more negative as climate develops into warmer and drier conditions, such as the drought-prone Mediterranean regions (e.g. Peñuelas et al. 2008, Linares and Camarero 2012, González de Andrés et al. 2018). The physiological basis of such pattern is linked to strong reductions of stomatal conductance resulting from water deficit (Waterhouse et al. 2004), which reduces cavitation risks at the expense of reducing photosynthesis and growth (McDowell et al. 2008). If drought is long or intense enough, drought-induced mortality could occur as a consequence of hydraulic failure or hydraulically mediated carbon starvation, and subsequent predisposition to attack from biotic agents (McDowell 2011).

An important issue when analysing climate change impacts on forests is the composition and structure as forest response at both tree and stand levels, which is greatly modulated by competing neighbours and stand structure (e.g. Coomes et al. 2014, González de Andrés et al. 2018, Grossiord 2019). In forests, trees compete for light, water and nutrients, and the effect of such tree-to-tree interactions may be more important than climate factors (Primicia et al. 2013, Fernández-de-Uña et al. 2016). In mixed-species forests, biodiversity effects can modify the performance of communities compared to individual species. Two main processes are thought to contribute to positive biodiversity effects (Fig.1): facilitation (positive effect exerted by one species on the functioning of cohabiting species, Bertness and Callaway 1994), and resource partitioning (differences in functional traits that reduce competition for resources, Hooper 1998). Facilitation and resource partitioning involve multiple mechanisms, including nutrient, water and light-related processes. A thorough list of such mechanisms can be found in Forrester and Bauhus (2016) and in Ammer (2018).

There is increasing evidence that biodiversity promotes various ecosystem functions and services (Cardinale et al. 2012). Tree species richness has been shown to foster productivity at both regional (e.g. Jucker et al. 2014, Vilà et al. 2013, Fichtner et al. 2018) and global scales (Zhang et al. 2012, Liang et al. 2016, Jactel et al. 2018). Mixed forests have been also found to be more stable in terms of biomass production (Morin et al. 2014, Aussenac et al. 2017, del Río et al. 2017) and resistant against disturbances (Jactel et al. 2017). However, mixing effects are modulated by environmental conditions (Ratcliffe et al. 2017, Mina et al. 2018), and special attention has been paid to climate (Forrester et al. 2016, Jucker et al. 2016, González de Andrés et al. 2017, Jactel et al. 2018). In fact, selective effects have been proposed to drive long-term forest responses to climate change, so that changes in competitive balance and species composition are expected to occur (Morin et al. 2018). It is noteworthy that positive biodiversity effects would take place as long as tree species interactions improve the mobilization of the limiting resource (Forrester 2014). In the context of climate change with predicting increasing aridity, mixtures will not display greater drought resistance unless net water-use partitioning or water-related facilitation processes occur (Grossiord et al. 2014). Hence, adaptation of forest stands to rising water deficit depends on functional traits – and thus identity – of species involved (e.g. Forrester et al. 2016, Metz et al. 2016, Tobner et al. 2016, Vitali et al. 2018, Yuan et al. 2018).

Apart from species composition, climate change impacts on forest functioning depend on nutrient availability (Lévesque et al. 2016). On one hand, elevated nutrient availability makes trees susceptible to suffer greater water stress as they likely increase water demand and reduce uptake capacity (Dziedek et al. 2016, Lim et al. 2015, 2017) due to higher investment to foliage biomass and increased shoot-root ratios (Marschner et al. 1996). Under high nutrients' trajectory, intensive droughts increase risks of cavitation and mortality due to hydraulic failure (Gessler et al. 2017). On the other hand, decreased nutrient availability and uptake, which take place during a drought event (Kreuzwieser and Gessler 2010), are worsen if nutrient content in forest soils are low, so increasing likelihood of C starvation and biological infections under long-term water deficit (Gessler et al. 2017).

At the same time, climate change also affects cycles of nutrient in forest ecosystems (Fig. 2). Litterfall constitutes a major proportion of nutrient cycling between plant and soils in forests (Presscott 2002). Climatic conditions are closely linked to variations in production, seasonal patterns and composition of litterfall (e.g. Aerts 1997, Blanco et al. 2006, 2008, Yuan and Chen 2009, Zhang et al. 2014, González de Andrés et al. 2019). Hence, projected increasing temperatures and alterations of precipitation regimes will have striking consequences on litterfall dynamics.

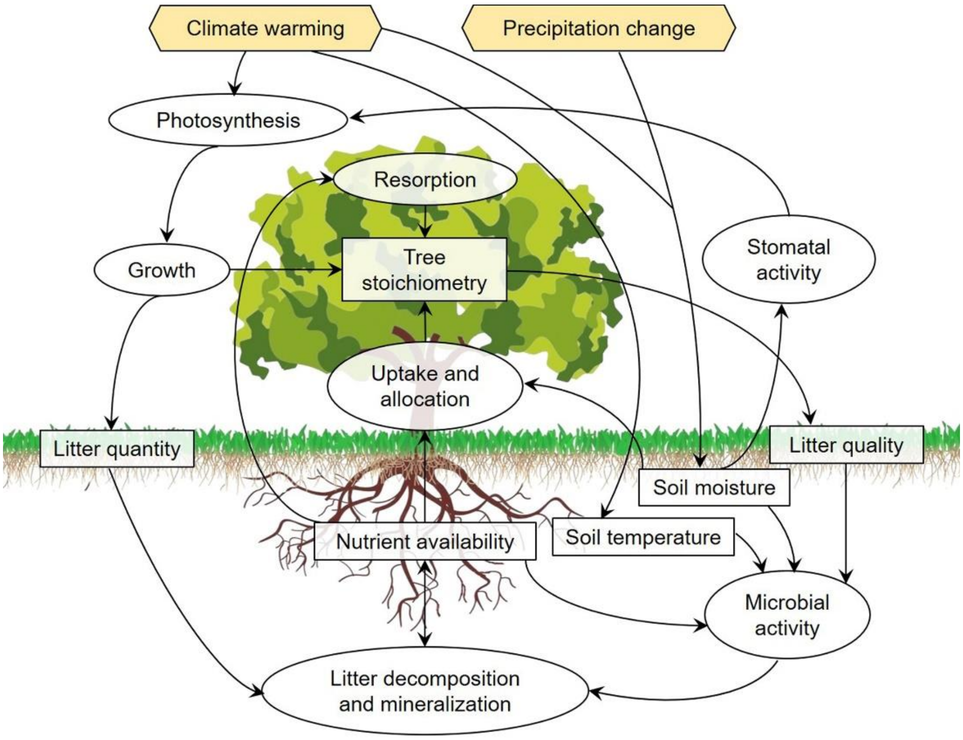

Figure 2. Conceptual diagram of the impacts of climate change on processes controlling stoichiometry of trees and nutrient cycling in forests ecosystems. Yellow hexagons are climate change drivers, rectangles represent nutrient pools, and ellipses indicate biogeochemical processes (own elaboration).

Stoichiometry (i.e. proportion of elements) of organisms and resources determine rates at which metabolic reactions take place (Sterner and Elser 2002). Elemental stoichiometry can be associated with important ecological processes and ecosystem traits, such as the ability of trees to adapt to environmental stress (Sardans et al. 2013, 2017), or composition of decomposer communities and litter decomposition rates (Güsewell and Gessner 2009, Mooshammer et al. 2014). Indeed, litter quality has been identified as the most important factor controlling decomposition (Cornwell et al. 2008, Zhang et al. 2008), which have been negatively related with high litter nitrogen:phosphorus (N:P) ratios (Güsewell and Freeman 2005, Mooshammer et al. 2012). Litter stoichiometry is the product of many processes, including nutrient uptake and allocation, growth, or resorption, which are modulated by climatic conditions (Fig. 2). In general, warming and drought have been proposed to increase tree N:P ratios (Yuan and Chen 2015), whereas N and P resorption efficiencies are reduced and enhanced, respectively (McGroddy et al. 2004). In addition, water availability largely determines the effect of rising *Ca* and N deposition on stoichiometry of nutrient recycling (Zechmeister-Boltenstern et al. 2015).

Decomposition and nutrient mineralization rates are also driven by climate (Parton et al. 2007, Zhang et al. 2008). For instance, drought decreases microbial activity in soils and ion mobility (Kreuzwieser and Gessler 2010). As well as, warming increases net N mineralization and nitrification and reduces soil P availability (Melillo et al. 2011, Dijkstra et al. 2012). Therefore, climate change is expected to have significant impacts on different processes controlling nutrient cycling in forests González de Andrés 2019).

In short, climate change will influence productivity, species interactions and nutrient cycling of forest ecosystems, all of which interact among them in a complex way. Understanding how climate factors affect different aspects of forest functioning is essential in order to predict forest responses on ecosystem services, and therefore how such services can contribute to reach the UN´s Sustainable Development Goals.

2.3 Climate change impacts on the relationship between forest biodiversity and ecosystem function

UN´s Sustainable Development Goal 14 is “Life Below Water” and SDG 15 is “Life on land”. Therefore, the maintenance of biodiversity in both water and land systems is a priority for development to be considered sustainable. The effects of environmental conditions on the relationship between biodiversity and ecosystem functioning (B-EF) are poorly understood. Most research on this topic has been carried out in grasslands although is rapidly increasing in forests. However, studies on plants predominate but research on other kingdoms is almost absent. Climate change may alter to which degree complementarity (i.e., niche partitioning and facilitation) and/or dominance effects underlie the B-EF relationship (Pires et al. 2018). Ratcliffe et al. (2017) explored the B-EF relationship along gradients of tree species richness using a European research platform that included boreal, temperate and Mediterranean forests. They found that water availability was the most important factor in changing B-EF. In general, B-EF relations tended to be more positive in water limited forests (e.g., Mediterranean) and to turn neutral or negative in forests with high water availability (e.g., boreal). Similar B-EF relations have been found in boreal forests when comparing limiting and non-limiting water conditions (Grossiord et al. 2014). These results add more evidence supporting that niche partitioning is an important mechanism in water-limited forests. Furthermore, as water limitation increases under climate change, biodiversity may become even more important to support high levels of functioning in European forests. However, biodiversity effects can also be negative in mixed boreal stands relative to pure ones in the sense that water availability can be more intensively used through niche partitioning in the former leading to lower tree growth (Grossiord et al. 2014). Also, if only a subset of species is resistant to the climatic stressors, and this selection or dominance process becomes increasingly important under climate warming, the complementary effects will probably diminish (Pires et al. 2018, Steudel et al. 2012).

It is also important to point out that changes in biodiversity and ecosystem functioning can affect global climate change (Hisano et al. 2018). Thus losses in biodiversity can directly reduce ecosystem functioning (e.g., losses in carbon stocks) which can accelerate global change (e.g., increased carbon emission). Moreover, increased biodiversity can mitigate the negative impacts of climate change on ecosystem functioning.

3. Synergies between climate change and ecosystem services

3.1 Ecosystem services in forests

Ecosystem services are the benefits humans receive from the environment, and a concept to explain beneficial functions provided by ecosystems to the society (Dai et al. 2017, Nolander and Lundmark 2016). In particular, forests ecosystems provide multiple and diverse services, resources, goods and products for human well-being and a great variety of purposes. The demand for ecosystem services is dynamic and influenced by societal transformations, political preferences and changing environmental conditions (Peters et al. 2015).

Traditionally, forest owners had a main economic interest in provisioning services such as manufacturing of wood products, timber supply, and pulp and paper production at the expense of other services (Duncker et al. 2012, Nolander and Lundmark 2016). Thereby, forests provide further services (e.g. preservation of biodiversity, carbon sequestration, water regulation, nutrients cycling, hydrological functions, recreation), and at the same time have to face increasing and recent environmental problems (e.g. global climate change, biodiversity loss, pollution, land degradation and desertification). Thus, current forest management options should provide economically valuable products or services and promote a good living environment (Dai et al. 2017), as well as to mitigate environmental pressures and improve long-term human well-being (e.g. socio-cultural or economic benefits such as health, employment and income).

Current sustainable forest management practices are expected to lead to beneficial trade-offs or synergies between different ecosystem services. Therefore, knowledge and awareness of interactions between ecosystem services are necessary for taking decisions regarding appropriate forest management. Trade-offs or synergistic relationships between the same ecosystem services will differ among forests due to different ecological processes at different scales (Dai et al. 2017). In recent years, there has been an increasing interest to use woody resources as an energy source and substitute for fossil fuels (Nolander and Lundmark 2016). However, there is also the need to analyze the effects of energy wood production and use in policy development and forest management in order to address current and future trade-offs and to take advantage of the full potential of synergies related to other forest ecosystem services. These trade-offs and synergies are difficult to predict since they are influenced by several dynamic factors, such as climate change, time and spatial scale, forest types, or specific local conditions. Stakeholders perceive similar trade-offs and synergies between energy wood production and provisioning (e.g. timber production, competition between material and energy use, marketability of wood, employment and rural development), regulating (e.g. climate, soil and water regulation, wildfire prevention), supporting (e.g. biodiversity and nature conservation, political regulations) and cultural (e.g. recreation) ecosystem services (Peters et al. 2015). It is also important to point out that management of natural resources creates an impact on the ecosystems that must be identified and quantified, in order to contribute to sustainable development.

3.1.1 Forests are Sources of Wood and Fiber

UN´s SDG 9 is “Industry, Innovation and Infrastructure”, whereas SDG 12 is “Sustainable Consumption and Production”. Forests have a long history of being important providers of economic material for human society (Golle et al. 2009). In the old times, timber production was one of the major goals in forestry. To increase the supplement of industrial wood, European countries and the United States started to establish forest plantations since the 18th century, while the rest of the world followed after World War II (Pandey and Ball 1998, Woziwoda et al. 2019). In the beginning, industrial forestry focused on monoculture and fast-growing plantations. However, with the awakening of the concept of ecosystem and its services, how to sustainably keep supporting human and other organisms’ needs became one of the major issues in forestry (MEA 2005). In addition, with the rising issues regarding climate change and its impacts, forestry is moving from supplying wood and fiber to mitigating climate change by reducing atmospheric CO_2 concentration. In this section, we discuss the differences between monoculture plantations and mixed forest plantations, and how climate change affects the production of these two management strategies.

Monoculture (i.e. one tree species plantation) has the advantage of being easy to manage with less cost (Heilman 1999, Lee 1999). Depending on the species and the final needs, the rotation length can be as short as 7 years to as long as 70 years (Pandey and Ball 1998). However, such intense and short rotations, cause soil fertility degradation, higher chance of erosion, higher susceptibility to fire, wind and insect disturbances, among other issues (Wei et al. 2012, Wei and Blanco 2014).

In central Europe, planting pure Scots pine (*Pinus sylvestris*) stands, which started in the 18th century, was the first major trend in forestry (Woziwoda et al. 2019), while in the USA, several other pine species were chosen for plantations. Later, fast-growing eucalyptus, pine and acacia species, as well as rubber and oil palm were also chosen for industrial tree plantation all over the world (Overbeek et al. 2012, Pandey and Ball 1998, Lee 1999, Onyekwelu et al. 2011). As forestry is trying to increase wood and fiber supply to meet human demands, the extent of world's forests continues to decline due to growing human populations and increasing demand for cropland. According to FAO´s 2015 Global Forest Resources Assessment, world forests have decreased from 4,128 million ha in 1990 to 3,999 million ha in 2015 (MacDicken et al. 2015). Among these forests, only 3.5 percent are plantation forests (Brown and Ball 2001).

Even though wood and fiber are still in high demand, with the perception change of other ecosystem function and services (MEA 2005), monoculture plantations have become less favored. For example, in Europe, mixed Scots pine plantations with Norway spruce or with broad-leaves species started to become the management trend since late 20th century (Woziwoda et al. 2019, Bielak et al. 2014). In other regions, mixtures of eucalyptus and acacia, or mixtures of conifer species with local native broadleaves have also been chosen to increase forest productivity or maintain biodiversity (Onyekwelu et al. 2011, Tchichelle et al. 2017, Paul et al. 2015, Wei et al. 2014). If the focus is on forest productivity, some recent studies show 20-30% overyielding of mixed versus pure stands in stand volume productivity in temperate and boreal forests (Morin et al. 2011, Bielak et al. 2014, Pretzsch et al. 2015). Thus, when compared to pure Scots pine stands, pine and beech mixed stands have higher stand volume, stand density, basal area growth, and stand volume growth, with increases ranging from 8% to 20% (Pretzsch et al. 2015) .

Although genetic biotechnology, silviculture practices and different management strategies can be used to improve forest productivity (Karoshi and Nadagoudar 2010), environmental factors play the major role to control forest productivity. Fig. 3 shows how environmental factors affect forest biomass production. In short, light, CO_2 concentration, and water directly affect photosynthesis rate, all together with other environment factors such as temperature, precipitation and soil nutrient plus stand condition (i.e. age or stage of development, stand density and species composition) determine the final amount of forest productivity (Lo et al. 2011, Blanco et al. 2016, Aguirre et al. 2019).

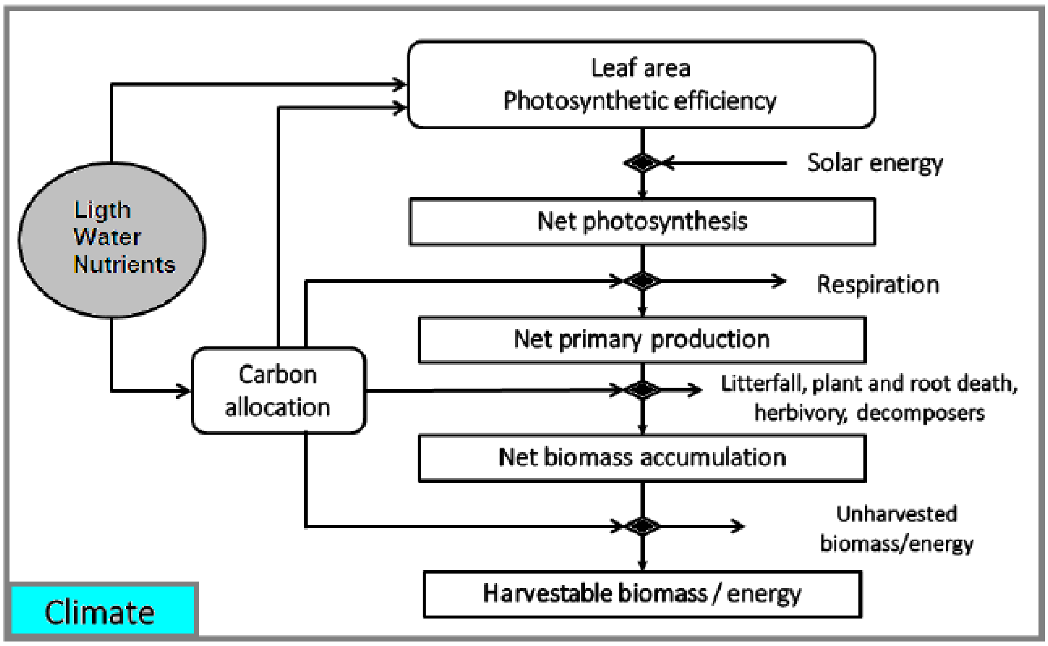

Fig. 3. Main limiting factors involved in the transformation of solar radiation into harvestable wood and fiber (own elaboration).

Even though climate change may increase forest productivity with increasing atmospheric CO_2 concentration and increasing mean air temperature (Lemordant et al. 2016, and section above), other environmental factors diminish this effect due to the lack of sufficient nutrients or to more severe and frequent disturbances such as drought, flooding, fire, insects and wind damages etc. (Klein and Hartmann 2018, Poulter et al. 2013, IPCC 2013, Girardin et al. 2016, Lo et al. 2019). Depending on the location and site condition, how to choose the proper species combination and management strategy become a major challenge in forestry oriented to meet UN´s Sustainable Development Goals.

3.1.2 Forests are Sources of Energy

UN´s SDG 7 is “Affordable and Clean Energy”. Enhanced environmental concerns are encouraging the use of renewable and alternative sources of energy, especially in developed countries (IEA Bioenergy 2002). Expansion of renewable energies is a key measure in climate change mitigation and reducing greenhouse gas emissions (de Jong et al. 2017), but the design of energy policies should identify options that reconcile national and international obligations to address climate change and the loss of biodiversity and ecosystem services (Holland et al. 2016). Besides, the expansion of renewable energy can be considered controversial regarding to land use competition and social acceptance, and entails trade-offs with nature and biodiversity conservation (Hastik et al. 2015). Meeting the world’s energy demand represents a major challenge for society over the coming century (Holland et al. 2016), and renewable bioenergy can improve the delivery of social, economic and environmental benefits from forestry (Dale et al. 2017). In this sense, there is increasing recognition of general environmental advantages of bioenergy (IEA Bioenergy 2002). The main drivers for bioenergy are the mitigation of global climate change, the increase in fossil fuel prices, and the concerns about energy security.

Bioenergy refers to the generation of renewable energy via the use of plant and animal based matter (Gasparatos et al. 2017). The main sources for providing bioenergy are forestry and agricultural residues or waste from different sectors (e.g. municipal and industrial waste, livestock, food, etc.). Bioenergy use differs notably in different regions: almost approximately 50% of energy supply in Africa comes from renewables as biomass sources, but only a percentage of 10% of the supply in Europe comes from renewable energies (WBA 2018). Increasing the contribution of bioenergy to total energy production can reduce their reliance on finite fossil fuel resources and help mitigate anthropogenic climate change. However, the increased use of bioenergy has potential implications for land management, biodiversity and ecosystem services (Ranius et al. 2018).

Forest bioenergy is typically a side product of forest harvesting and wood processing. It is generally produced as a complementary co-product of wood and fiber products as sawlogs and pulpwood (Berndes et al. 2018). It is unusual for forest bioenergy to be the sole product from harvested wood (Matthews et al. 2014). In general, biomass for energy has a lower bulk density and economic value than wood for timber or paper and pulp industry (Abbas et al. 2011), so that bioenergy systems often use biomass that would otherwise be unmarketable (IEA Bioenergy 2002). Forest bioenergy must be considered as an integral part of forestry-industry-energy systems (Berndes et al. 2018). In this context, an integrated production system for wood and bioenergy exhibits an example of synergy as the thinned stand maximizes the value of wood products, and thinnings are used for bioenergy.

Biomass is the most widely used fuel in underdeveloped countries (Mateos et al. 2016). Fuel wood or charcoal are still used for heating and cooking, mainly in developing countries, whereas large quantities of industrial wood and forest wastes are used to generate energy in developed countries (IEA Bioenergy 2002). Characteristics of different regions and countries need to be taken into account to develop long-term and far-reaching political frameworks (Peters et al. 2015).

Interest in the utilization of forest biomass for energy is growing due to environmental reasons, such as concerns about climate change and energy security, promotion of innovative bio-based industries and policies to displace non-renewable resources. During the last decades, European energy demand has increased and it is expected a further increase in future years due to socio-political changes (Peters et al. 2015). Predictions indicate a significant increase in the use of biomass for transport, indoor heating, electricity generation and diverse industrial processes (Börjesson et al. 2017). At the same time, renewable energy polices in the European Union (EU) have developed gradually since the 1990s, setting a long-term goal to develop a competitive, resource-efficient and low carbon economy by 2050 (European Commission 2011). In parallel, European countries have developed and implemented different policies to promote the production and use of bioenergy from forests (Lindstad et al. 2015).

Sustainable forest management focuses on the balance between various economic, ecological and social functions and is key to maintaining healthy and productive forests (Hastik et al. 2015, IEA Bioenergy 2018). Managed forests are considered strategic areas for the importance of storing carbon and providing a continuous stream of ecosystem services, including wood products, energy and biodiversity conservation (Nabuurs et al. 2015). Conventional forest industry focuses to produce high value products, such as saw-wood and wood panels, or pulp and paper, but residues and by-products have typically been used for energy. Consequently, forest managers take advantage of low value stemwood from short rotation periods, thinnings, and diseased or low quality trees to generate bioenergy (IEA Bioenergy 2018). The energy valuation of biomass also improves the forest economy, and provides ecological benefits and other additional advantages, such as the generation of employment in rural areas or reduction of forest fire risks (Mateos et al. 2016).

Forest biomass for bioenergy is commonly referred as woodfuel (Matthews et al. 2014). Woodfuel can be classified in different types of products used as fuel for different energetic purposes such as cooking, heating or power production. Forest industry develops different types of forest biomass to be available for energy uses, such as logs, briquettes, wood chips, pellets, or charcoal. These woodfuel products present diverse sizes, shapes and consistency to meet bioenergetic demands (e.g. domestic or commercial heating, power generation at different scales, generation of steam and electricity in the service industry) or non-fuel uses (e.g. food smoking, animal bedding). Global wood pellet demand has experienced a recent growth that has been driven largely by EU renewable energy targets to reduce greenhouse gasses emissions (Dale et al. 2017). Europe is the world leader in pellet production (WBA 2018). The EU and individual countries bioenergy policies promote biomass sustainability policies that stimulate pellets market, such as tax exemptions, mandatory targets, electric power feed-in tariffs, or direct subsidies (Dale et al. 2017). Charcoal is also an important source of renewable energy with great industrial importance in the world. Charcoal is produced via the partial burning of biomass, and it is used as domestic fuel or chemical product, but it also can be used in agriculture (e.g. soil amendment) and industrially (Rodrigues and Braghini Jr. 2019). The charcoal sector is underestimated due to the traditionally informal trade of the product. Charcoal is produced and consumed locally, unlike pellets and liquid biofuels.

Moreover, the process of conversion is a highly inefficient process (WBA 2018). However, all these woodfuel products for bioenergy provide a renewable alternative to fossil fuels.

Current industrial processes homogenize and prepare woodfuels for the market and reduce the differences in heat power among different tree species, it is almost irrelevant which the composition of the forest is. It is much more important which forest operations are applied, as during those operations (pruning, thinning, partial harvesting, clearcutting, etc.) residual biomass that can be used for bioenergy is generated. Therefore, bioenergy from the forest is easily incorporated in modern near-to-nature and mixed forests management, which can support the contribution of forest management to reach UN´s Sustainable Development Goals.

Many and diverse reasons are argued for promoting energy wood, such as its renewable and storable characteristics, the increase in security and diversity of energy supply, or its relatively low and less volatile prices compared to fossil energy sources (Peters et al. 2015). Moreover, the use of wood for bioenergy can also provide multiple environmental benefits (Dale et al. 2017) such as climate change mitigation (Berdndes et al. 2018) and employment to local people. On the other hand, impacts caused by the increase of biomass energy production are related to forestry practices, transport activities and infrastructures. For example, large-scale biomass production can result in site compaction, runoff, soil erosion, or loading of sediments and nutrients to water bodies (Abbas et al. 2011) resulting in unexpected tradeoffs (Peters et al. 2015). Aspects such as conversion efficiency into energy products, cost efficiency, biodiversity issues, soil carbon and nutrient balances also need to be considered when extracting energy wood (Nabuurs et al. 2015). Therefore, the development of policies and forest management strategies for bioenergy must include potential trade-offs and synergies between biomass production, changes in ecosystem structure and function and forest ecosystem services.

3.1.3 Forests are Sources of Food

UN´s SDG 2 is “Zero Hunger”. The elimination of hunger and malnutrition from human-being population, or, the increase in food security, is one of the sustainable development goals of the United Nations. The World Food Summit held in 13-17 November 1996 in Rome, Italy defined food security in the “Rome Declaration on World Food Security” as “the right of everyone to have access to safe and nutritious food, consistent with the right to adequate food and the fundamental right of everyone to be free from hunger”[2]. Although the major problem of malnutrition in the world is undernutrition with an estimated number of 821 million people in 2017 (FAO et al. 2018), the problems of overnutrition and micronutrient deficiencies are also affecting health, especially

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[2] FAO (1996) Declaration on world food security. World Food Summit, FAO, Rome http://www.fao.org/3/w3613e/w3613e00.htm

in some rich countries. Efforts on food security as such, therefore mean not just the supply of sufficient food for everyone but also the diverse food resources that the give multiple nutrients/micronutrients needed for a healthy life.

Modern agriculture systems that feed the majority of people rely on intensive use of croplands for producing staple food and vegetables. On the other hand, there are still diverse food sources growing in the forests and about 20% of the world population are partially depending on them while millions of indigenous people are fully dependent on these foods (Vira et al. 2015). Stadlmayr et al. (2013) reviewed the tree products used by indigenous people in Africa and indicated their high nutrient values. People living in the environment with higher forest coverage have higher access to diverse and nutritious foods (Ickowitz et al. 2014). Therefore, dietary sources from forests may provide those people with important micronutrients (Ickowitz et al. 2016). While forest tree species that produce edible parts could be utilized by collecting them during the suitable seasons, some species may potentially be further cultivated and breeded to reach higher production rates (Jamnadass et al. 2010).

Forests are important protein sources as well for some tropical inhabitants (Nasi et al. 2011). People living in the rural areas of the Amazon for example, consume ca. 60 kg bushmeat annually per person (Nasi et al. 2011). For some regions, the bushmeat could be the only animal protein source because meat from husbandry of the typical meat-providing animals is not available. Except bushmeat, forests also provide animal proteins from fishes and insects to those people who have access to these resources.

Besides the direct provisioning of foods by forests, diverse traditional medical resources are used from wild animals (Alves and Alves 2011) and plants (Uprety et al. 2012). Trees and shrubs also provide fodder for livestock (Pimentel et al. 1997). Moreover, for many people living in developing countries, fuelwoods could be collected from forests for cooking. Without sufficient fuelwoods, some raw food materials are just not feasible for consumption and therefore the potential provisioning service of food will not be reached (Makungwa et al. 2013). In agricultural landscapes, the woodland/forest patches could help maintaining vigorous populations of crop pollinators (Winfree et al. 2008, Koh et al. 2016). In a recent synthesis work, Reed et al. (2017) recognized that forests can maintain or enhance yields compared to monoculture system in the tropics, although research in larger spatial and temporal scales are still needed.

In climate change scenarios with increasing temperature and changing precipitation regimes, together with increases in deforestation, forest fragmentation, the loss of biodiversity and the spread of invasive species, the food availability from forest are expected to be changed (Vira et al. 2015). For people relying on the food from forests for their daily life, the impact of global environmental changes will be drastic (Paumgarten et al. 2018). However, for those who feed on agricultural products and live in the rural areas where original forests are accessible, the climate change-induced reduction of crop yield might be partially compensated by the foods from forests. Woody tree species in the forests usually are more resistant to changing weather conditions between years than the annual crops because of their nutrient storage in the tissues. The high diversity of tree species in a natural forest usually implies a high diversity of fruit types, different timing of fruiting (phenology), and different water use efficiency, which, potentially may safeguard the food provision through the year under adverse weather conditions (Vira et al. 2015).

3.1.4 Forests are Sources of Water while Stabilize Soil

UN´s SDG 6 is "Clean Water and Sanitation". Thousands of millions of people suffer the effects of inadequate access to water (Mekonnen and Hoekstra 2016). In many regions of the world, excessive exploitation of hydrological resources, inadequate water use and pollution are increasing threats for water availability and quality for agricultural, industrial or urban uses (FAO 2009). Climate change can exacerbate water scarcity and threaten food security, becoming a main driver for massive migrations and increased social and political conflicts (Kelley et al. 2015). Forests play an integral role in water quality and availability for different uses, as well as in stabilizing and protecting soils from erosion. Most drinkable water in the world originates in forest-covered watersheds, and forests protect many reservoirs from being silted. In addition, forests also protect underground waters from pollutants due to forest soils filtering capabilities (FAO 2009). Both soil and water are essential elements for tree growth and health, as well as for the rest of organisms that inhabit forests. However, due to an increasing water demand for urban, agricultural and industrial uses, as well as land for urban development caused by increasing human population and consumption, forests are usually under strong pressures. Such pressures will be exacerbated in many regions of the world due to climate change (Blanco 2017).

At global scale, forests play an important role in regulating atmospheric both water flows and precipitation patterns on landmasses (Ellison et al. 2017). On land surfaces, passive water evaporation by heat is joined by active water transpiration by plants, which take water from the soil to release it to the atmosphere as a way of moving their own internal fluids. Such evapotranspiration usually accounts for at least 40% of precipitation on landmasses, reaching up to 70% in some tropical humid forests (Van der Ent et al. 2010, Jasechko et al. 2013). The resulting atmospheric moisture circulates around the globe with the winds, redistributing water among different continents (Ellison et al. 2017). Although traditionally the relationships between forests and water have been understood in the framework of the hydrological cycle at watershed level, such view fails to recognize the connections among watersheds due to precipitation recycling. For example, it has been proven than in tropical regions, the same moist air over forested watersheds can produce twice as much precipitation than over sparse vegetation (Spracklen et al. 2012). On the other hand, forests can promote precipitation by generating particles and aerosols (bacteria, pollen, spores, canopy fragments), which can work as condensation nuclei for water vapor (Sheil 2014). Due to these teleconnections among watersheds, with increasing deforestations, sites further away from coastal winds would be the first ones exhibiting changes in predictability, extension and amount of precipitation. Such changes can even produce a switch from humid to dry climates in ecosystems in the ecotone between such climatic zones (Sheil and Murdiyarso 2009). In fact, the new theory of the "biological pump" suggests that normal wind circulation from ocean to continents is mostly due to low pressures created by forests over landmasses as consequence of their evapotranspiration (Makarieva et al. 2013). If this is true, severely modifying forest cover could change wind patterns at regional or even continental scales, and therefore affect spatial precipitation distribution (Sheil and Murdiyarso 2009).

In any case, the connections between forests and water are much more evident at local scales. Rainfall intercepted by canopy and evaporated from leaves and branches reduces the direct conversion of precipitation into runoff and underground water, and transpiration by plant leaves increases this reduction. Although such reductions in "blue" water flows could be considered as losses for water production in forested watershed, it must be taken into account that trees produce "green" water contained in timber, fiber, flowers, fruits and seeds (Calder 2007). Hence, although there is no doubt that forests use water, they also produce many goods and services needed by human societies (FAO 2009, see previous sections in this chapter).

On the other hand, forests can actively intercept water vapor, fog and clouds, creating the so-called "water towers" (Vivorili and Weingartner 2004). These towers consist of forests areas at high altitudes that catch water and fog when they condense on plant surfaces (Bruijinzeel 2004). In fact, fog forests can generate more water for the root zone that other forest types with similar precipitation levels (Caballero et al. 2013). Hence, such "water tower forests" can become important water sources for downstream regions (Muñoz-Villers et al. 2015). For example, the Andean Yungas are the main water source for 40.000 ha of irrigated farmland and two million people (Malizia et al. 2012). Fog forests are also highly efficient capturing water as they are composed by a high variety of plant forms (Valencia-Leguizamón and Tobón 2017), and therefore the conservation of their biodiversity should be a priority (Ochoa-Ochoa et al. 2017). In addition, water provision by fog forests is important not only in amount, but also in temporality, and it can reach up to 75% of total available water during dry season in some areas (Bruijinzeel et al. 2011). For example, in dry regions in southern China, up to 80% of precipitation during the dry season appears as fog (Liu et al. 2004). Such temporal regulation of water flows by forests will be even more important under climate change, as rainfall unpredictability and extension of dry season will be the norm in many forest regions around the world.

Forest also have important roles in arid regions. In many parts of the world, especially in climates with dry seasons, water flow regimes are more important that total water available annually to sustain both aquatic and terrestrial ecosystems and agricultural and industrial activities (Bruijinzeel 1990). Water flow in streams during the dry season is vital for navigation, wildlife, rural communities, cattle, fisheries and particularly for irrigation systems without technology to pump underground water (Aylward 2005). Therefore, flow-regulating services by forests in arid regions can be more important than total water yield downstream (Sandström 1998). Many arid and semi-arid regions suffer also from overexploitation of their plant and soil covers, generating erosion and desertification issues. Therefore, restoring forest cover with a diverse plant and tree community is vital to recover hydro-ecological services or at least to avoid worsening water availability issues (Bargues Tobella 2016).

The relationship between forest management and water availability downstream is not clear. Traditionally it has been assumed that removing forest cover increases water yield downstream as the evapotranspiration is drastically reduced. There are strong evidences supporting this assumption, as the works by Bosch and Hewlett (1982) and Grip et al. (2005) have shown. However, this assumption may not be true for tropical fog forests or boreal conifer forests, which can store and intercept important amounts of water as snow or fog (Buttle et al. 2000). Hence, the actual balance among the different components of the hydrological cycle in forested regions depends on precipitation, evapotranspiration and runoff (Balvanera 2012). However, this traditional paradigm that states that the less forest cover the more water downstream is being challenged, as it does not take the particularities of recharge, seasonality and recycling of water flows (Ellison et al. 2017). In any case, gains in water yields downstream after harvesting can be temporal, as ecosystem always transform and succession (or active landscape management) takes place.

Forest species composition is also an important tool to actively manage water use by forests. Different tree different species vary in their use of water as they reach different soil depths or are most active at different times of the year (Jones et al. 2018). Forest stands of mixed species may display complementary water resource use and they can reach higher use efficiency both in temperate and tropical climates (González de Andrés et al. 2018, Forrester 2015). Therefore, mixed-species forests may be more resilient to drought than monoculture plantations.

In any case, how forests affect the hydrological cycle would also be altered by global change. The main determinants of change in the forest-water relationship related to climate would be firstly precipitation, as it is the most robust single determinant of stream flow (Sun et al. 2011). Changes in both the amount and seasonality and storminess of precipitation can alter water yields downstream of forested regions (McNulty et al. 2018). Other factors that will alter the hydrological cycle under global change are air temperature modifications, as tree water demand increases with increased temperature (Zhang et al. 2015). Wind speed is another factor that can influence forest evapotranspiration. A recent slowing down of wind speed in the northern hemisphere has been attributed to increased roughness of forest canopy as consequence of changes in forest cover (expansion, reforestation) and forest composition (species, age cohorts) (Vautard et al. 2010). Also, atmospheric pollution can first reduce water yield as nitrogen deposition stimulates tree growth and therefore evapotranspiration (Quinn et al. 2010). However, such effect quickly reaches its peak as soils become N-saturated, causing among other effects tree mortality (which in turn increases streamflow, McNulty et al. 2014). In addition, water quality drops when leachable nitrate reaches streamflow (Aber et al. 1989). Other pollutants such as nitrogen oxides and volatile organic compounds are precursors of ozone formation, which in turn damage stomata, making trees less efficient using water (McLaughlin et al. 2007). All these changes can be modulated in mixed forests, as different tree species differ in their sensitivity to changes in temperature, wind speed or pollution. This effect makes mixed forests more resilient to climate-change induced alterations of the hydrological cycle than monospecific forests, and particularly even-aged tree plantations.

3.2 Relationships between Ecosystem Function, Species Traits and Ecosystem Services

Essentially, functional traits are attributes of organisms that influence their fitness. They can be of different nature: morphological, physiological, phenological, or even behavioral when concerning animals, but must be well defined and measurable (Blaum et al. 2011, McGill et al. 2006, Violle et al. 2007). Moreover, functional traits are often easily measurable; some typical examples in plant research include seed size, lifespan, maximum height, age at maturity, leaf mass per area, nutrient concentrations and stoichiometries, wood density or specific root length (fine root length per mass). Functional traits show intra- and interspecific variability depending on external factors such as the environment or the interaction with other organisms, and through this plasticity, we can measure responses to biotic and abiotic conditions.

The key benefit of using the functional trait approach is that it helps us to establish general rules in community ecology, including forest research (McGill et al. 2006). For example, to conclude that *Populus alba* grows faster than *Quercus robur* is less useful than saying that, in general, tree species with higher wood density have a lower growth rate (e.g. Kunstler et al. 2016). In addition, functional traits influence ecosystem processes (Violle et al. 2007, Westoby and Wright 2006), which allow us to use them to evaluate ecosystem services. It is being increasingly recognized that a functional approach, based on functional diversity or traits, explains better the ecosystem functioning and properties than focusing on species diversity (e.g. Gagic et al. 2015, Nadrowski et al. 2010).

In forest research, seed mass, leaf mass per area, wood density and maximum height are considered key traits. Especially wood density stands out as a highly informative attribute when trying to explain demographic rates (Poorter et al. 2008, Wright et al. 2010). Other traits can be linked to forest resilience as they are related to plants hazard tolerance. For example, germination phenology, growth form or shoot height are response traits to fire (Lavorel and Garnier 2002), while stature and architecture are related with grazing tolerance (Díaz et al. 2006).

Assessment of ecosystem services can also be done using this approach. The set of functional traits related with carbon cycling can be used to evaluate forest carbon sequestration. Key traits in this regard are growth rate, lifespan or litter C/N ratio (De Deyn et al. 2008). Water cycling is influenced by canopy architecture and litter production by means of regulating infiltration, runoff or rainfall interception (Westoby and Wright 2006). Canopy traits are also often linked to climate regulation while the root size and architecture affect soil stability (de Bello et al. 2010).

Research on the assessment of ecosystem services by means of evaluating functional traits has found this methodology as promising, and that the models created this way are usually more useful than those using only species diversity or abiotic variables (de Bello et al. 2010, Gagic et al. 2015, Lavorel et al. 2011). However, still exists some knowledge gaps where further research could focus. Mainly, current studies are biased towards particular trophic levels and services (especially plant communities and pollinators). However, the relationship between traits and services are often complex, with one trait affecting several services and vice-versa, creating possible trade-offs and interactions (de Bello et al. 2010, Lavorel et al. 2011). In this context, the evaluation of one trait will often not be enough: ecosystems complexity prompts us to use a bigger set of traits in order to improve our models (Wright et al. 2010).

Complexity in forests due to multiple species interactions is also a field where the functional approach has proven to be useful. Species coexistence, and in last term biodiversity, can be promoted by strategy specialization through trait differentiation (Kraft, Godoy and Levine 2015, Kraft, Valencia and Ackerly 2008). Functional traits play a key role in community assembly, for example, regulating how different organisms interact to create the biological community (Kunstler et al. 2016). The way in which functional traits synthesize ecosystem functioning makes them an essential tool for managing forests, especially at a time when complex, mixed species forests are increasingly being favored over monospecific ones.

3.3 Climate Change Impacts on Ecosystem Services

Climate change represents an important threat for forests (Lindner et al. 2010). In many regions, climate change will reduce water availability by increasing evapotranspiration (Blanco 2017). In addition, forest fires will increase in severity as consequence of reduced relative humidity, increased temperatures and increased wind speeds. Also, torrential rainfall will be more common, causing erosion and flooding events. As wind speeds will be increased in an atmosphere with more energy, windthrow events will be more common, causing more episodes or wind-related mortality. Pest and pathogens, whose life cycles are usually linked to dead or sick trees (weaker and with less defenses) and to climate conditions as number of generations per year depend on degree-days accumulated during the growth season will become more frequent and reach higher population peaks. Similarly, phenology of most plants (including trees) is tightly linked to temperature and water availability, and therefore it will be modified as climate changes advances (Chmielewski and Rötzer 2001).

These six effects combined will be translated into loses of stability in forest stands, regeneration being altered and biomass being lost. In other words, climate change will modify local environmental conditions, affecting trees´ ecophysiology (Saxe et al. 2002, Morin et al. 2010), demography (Hansen et al. 2001, Benavides et al 2013), and in the long term, their geographic distribution (Peñuelas et al. 2007, Lenoir et al. 2008, Urli et al. 2013). Changing tree species distributions may cause as some species will be able to “scape” climate change´s worst effects by moving into regions with environmental conditions more favorable. However, in trees such possibility is reduced due to their long life cycles and their limited dispersion capacity (Jump and Peñuelas 2005, Jump et al. 2006). Hence, it is expected that climate change will produce changes in forest communities’ composition, altering forest function (Kumar 2010).

As ecosystem services provided by forests are a reflection of how forest ecosystems work, any modification caused by climate change will impact on how such ecosystem services are provided. For example, reduction of forest biomass will have a direct impact in the provisioning of wood, fiber and bioenergy. However, effects on other ecosystem services will not be necessarily linear. For example, a reduction in tree biomass could translate into a more vigorous growth of the understory, producing more fruits or habitat for some game species, which then could increase food provisioning. On the other hand, if tree fruits are a main food source in the region (i.e.

chestnuts), such food source would be diminished. Other changes could be even more difficult to predict, or they could not be constant. For example, many edible mushroom species in the forests depend on coarse woody debris and litter to grow. If tree mortality were increased by climate change, dead wood would increase and cause a temporal increase in mushroom yields, but as mushrooms and mostly symbiotic entities that also depend on alive trees, such increase would be temporal. Similarly, water provisioning may be increased or decreased (or not being impacted) by changes in the forests, depending on tree species, topography, soil, etc. (Jones et al. 2018). Such difficulty in predicting impacts of climate change is mainly caused by the site-specific nature of many of these ecosystems services, and particularly cultural, recreational and spiritual services that depend not only on the forests but also on the people living in the region or with access to those forests.

4. Scaling up from ecosystem function to human well-being

UN´s Sustainable Development Goal 3 is "Good Health and Well-Being". Three case studies are presented as examples of representative ecosystems of boreal, temperate and tropical ecosystems. In all of them emphasis is put on synergies between climate change and other direct drivers, biodiversity, ecosystem function and services, indirect drivers of change and human well-being in forests. They illustrate how the relationships of humans with forests, which are dynamic and complex, are strongly influenced by the ecological-socioeconomic background and the drivers of change. Despite of this, common patterns and processes emerge which are the base, as many studies are showing, to improve human well-being.

4.1 Case study: Boreal Forests in China

Boreal forests, or taiga, are distributed across the high latitudes of the northern hemisphere. The north-south width of the boreal forests ranges from above 500 to 2300 km in Eurasia to above 1000 km in North America (Larsen 1980, Archbold 1995 in Hendrick 2001). The northern edge of the boreal forest correspond roughly to a July isotherm of 13ºC. The southern border generally follows an 18ºC July isotherm (Hendrick 2001). Common genera include the conifers *Picea*, *Abies*, and *Pinus*, and the hardwoods *Populus*, *Betula*, *Sorbus* and *Alnus*.

The Greater Khingan Mountains are situated in northeastern China in the only cold temperate zone in the country. The forests on the Greater Khingan Mountains form the southern boundary of the boreal forests in NW Asia and are dominated by *Larix gmelinii* (Editorial Committee for Vegetation of China 1980) (Fig. 4). The mean annual temperature is about -3°C and the mean monthly maximum and minimum temperatures are 17 to 20°C and -20 to -30°C in July and January, respectively. Between 330 and 1,750 m.a.s.l., the annual precipitation ranges from 350 to 500 mm, most of which falls in May to October. Snow pack averages 300-500 mm and lasts for 5 months. The frost-free period is less than 100 days. Slopes in the region are moderate, being the average slope 10°. Permafrost commonly occurs at about 5-40 m, and the maximum depth can reach 120 m. The soil type is predominantly a dark brown forest soil. Other tree species include white birch (*Betula platyphylla* Suk.), aspen (*Populus davidiana* Dole), Scots pine (*Pinus sylvestris* L. var. *mongolica* Litv.) and Korean spruce (*Picea koriensis* Nakai) (Xu 1998). There are about 180 species of common plants under the *Larix gmelinii* forests. Based on the understory, ground vegetation composition, edaphic and topographic conditions (Wang et al. 2001), eight main ecosystems are recognized in *L. gmelinii* forests on the Greater Khingan Mountains:

- *L. gmelinii–Ledum palustre* forests that grow on mesic toe-slopes;
- *L. gmelinii*–grass forests that grow on the fertile mid-slopes;
- *L. gmelinii–Rhododendron dahurica* forests that grow on the dry infertile steep slopes;
- *L. gmelinii–Pinus pumila* forests that grow in sites with harsh conditions,
- *L. gmelinii–Quercus mongolica* forests that grow on the fertile lower-slopes;
- *L. gmelinii–Sphagnum–Ledum palustre* forests grow in the wet, cool, and infertile sites;
- *L. gmelinii* riparian forests grow on the banks of rivers and streams under mesic and fertile conditions; and
- *L. gmelinii–Bryum argenteum–Sphagnum magellanicum* forests grow in waterlogged soils.

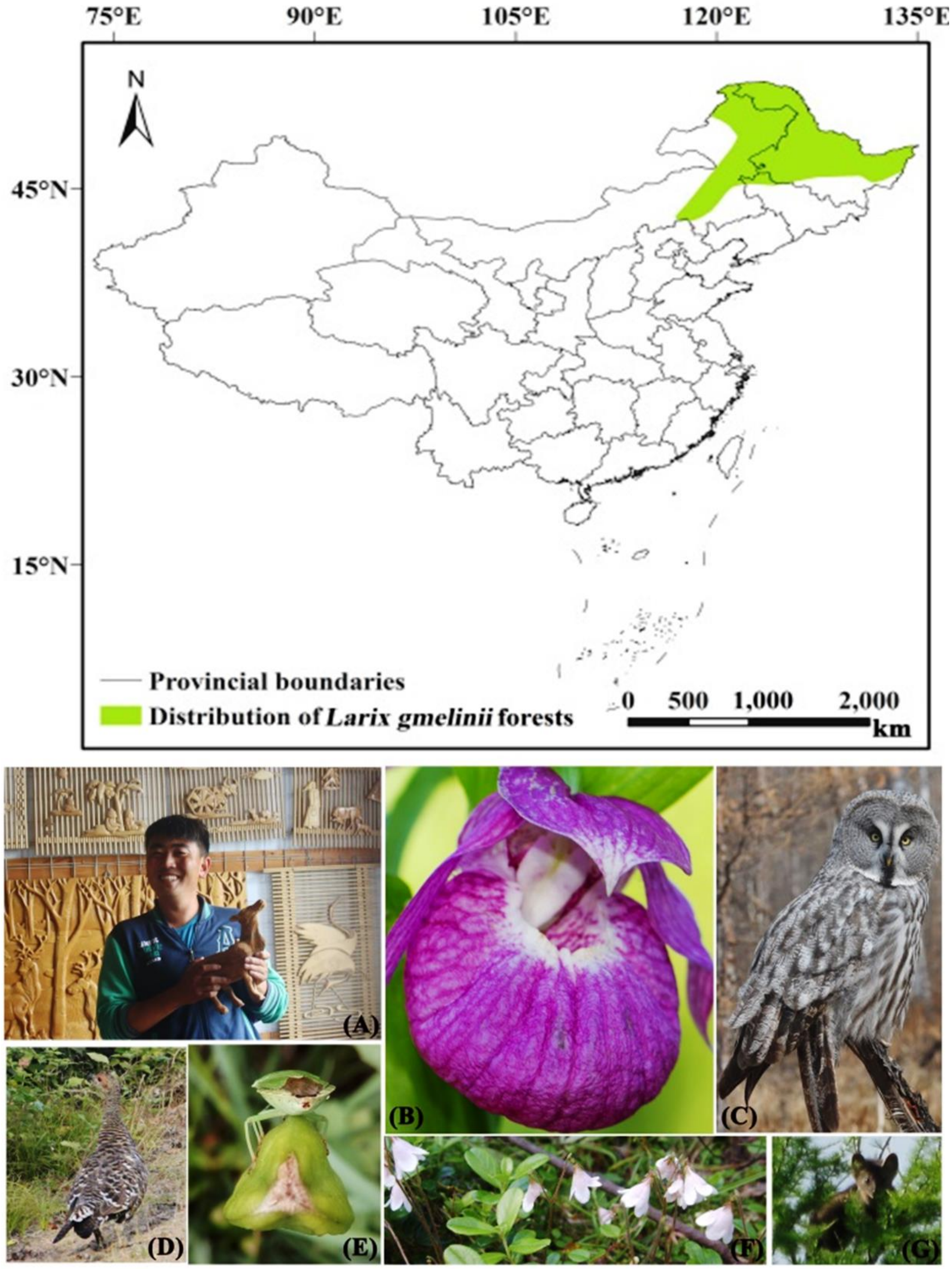

Fig. 4. Location of natural *Larix gmelinii* in the Greater Khingan Mountains, Northeastern China, art wares (A) produced by *Larix gmelinii* and boreal forests biodiversity: (B) *Cypripedium macranthum* Swartz; (C) *Strix nebulosa*; (D) *Bonasa bonasia*; (E) *Pantatomidae*; (F) *Linnaea borealis* L.; (G) *Martes zibellina princeps* [photos reproduced, with permission, from Y. Liu (A), J. Zhou (B), Y. Zhang (C and G) and R. Gao (D, E and F)].

The ecosystems of the Greater Khingan Mountains provide a range of goods and services for people. These include: (1) building materials: *Larix gmelinii* trees can reach up to 30 m in height and 60–80 cm in diameter at breast height, providing an excellent building material; (2) abundant medicinal plants such as *Schisandra chinensis, Sanguisorba officinalis, Bupleurum sibiricum, Trollius ledebouri*, and *Pyrola incarnata*, and endangered, precious and rare plants such as *Glycine soja, Astragalus propinquus* Schischkin, and *Phellodendron amurense*; (3) industrial crops for oil and fabrics: given its geographical location, soil, and climate conditions, the region of the Greater Khingan Mountains is especially suitable for large-scale planting of *Linum usitatissimum* L. and the *L. usitatissimum* plants grown here show vigorous growth, high yield, and good quality for textile and fiber industries.

Three river systems (the Heilongjiang, Nenjiang, and Argun Rivers) and more than 30 tributaries with a stream length >50 km originate in the Greater Khingan Mountains. *L. gmelinii* forests in these mountains play a significant protective role in water conservation and the maintenance of ecological water balance. *L. gmelinii* forests are the most important water conservation forests on the Songnen Plain and the Hulunbuir Grassland, Inner Mongolia (Li 2014).

Forests in this region also influence nutrient flows. The leaves of understory shrubs and herbs in *L. gmelinii* forests are usually evergreen, which is an adaptation to the snowy conditions and short growing season. Because the region is in a cold temperate zone and is covered with thick snow in winter, the snow protects the understory plants on the ground in an evergreen state over winter. Plants that overwinter in such a state can start photosynthesis and growth rapidly when the spring comes. These plants cover the land exposed by snowmelt, effectively reducing runoff and allowing the soil and its nutrients—such as nitrogen (N) and phosphorus (P)—to be preserved. The commercial harvesting of natural forests was halted in the Greater Khingan Mountains on April 1st, 2015. This measure has protected the biodiversity and reduced the melting of the permafrost layer in the region. The canopy interception of precipitation has increased and the proportion of precipitation entering rivers via surface and underground runoff has decreased. Soil nutrients are retained longer. The supply of soil nutrients not only promotes the growth of the forests and the understory shrubs and herbs, but also facilitates the regeneration and restoration of vegetation, thus effectively conserving biodiversity.

Finally, the forests in this region also have an important cultural and recreational function. Inspired by the cultural resources from “green ecology” in the Greater Khingan Mountains, the local government has built a sociocultural system around forest medicine and green food. For example, edible fungi, edible wild herbs, and red beans are produced on a large scale. People advocate a lifestyle that is closer to nature. Forests serve as an oxygen source, and natural areas including the Moerdaoga Forest Park and the Alihe Forest Park are preferred choices for vacations. Here, people can fully experience the beauty of the landscape provided by forests and trees.

However, these forests are also facing indirect drivers for change. From the socio-economic point of view, the forests of the Greater Khingan Mountains also produce wood for local residents. The wood delivers an ecosystem service to humans in the form of building materials and furniture. Wood provides enormous economic benefits and plays a crucial role in China’s socialist system, producing an important pressure to increase timber yields to maximize benefits. However, as the forests of the Greater Khingan Mountains offer other ecological benefits, and these forests form an irreplaceable natural ecological barrier in northern China, maximization of their ecological benefits is dependent on their biodiversity.

In this region, the most practical strategy for implementing biodiversity conservation is to establish nature reserves (Li 1993). The aim of establishing such reserves in the Greater Khingan Mountains is to protect and improve wildlife habitats, and creating a habitat protection network based on nature reserves is the main focus. However, nature reserves have changed the traditional lifestyle of farmers in the surrounding areas. The establishment of these reserves has negatively affected the local society and economy of the Greater Khingan Mountains by reducing their access to the forest, thus influencing the well-being of the farmers. The Chinese government has proposed two measures to address this: (1) local farmers are allowed to collect non-wood forest products such as wild Chinese herbal medicines, pine nuts, agarics, mushrooms, and blueberries but must not damage the nature reserves. This measure can increase the economic income of farmers and simultaneously protect biodiversity. (2) Farmers who depend mainly on the forest for their livelihood are given some economic compensation to increase their income. Ecotourism can be carried out in nature reserves to increase employment opportunities, farmers’ income, and local government revenue (SFAPRC 2016).

In addition, Because of the unique advantages of the forests in the Greater Khingan Mountains, the cultural value of this region can be promoted and publicized in the following ways: establishing a forest cultural and specimen museum to display forest products and trees in physical and picture forms; initiating activities with the theme of forest biodiversity conservation—such as forest photography, forest exploration, and forest health—to give everyone an opportunity of walking into the forest, feeling its beauty, and stimulating a desire and enthusiasm for nature. Additionally, people can produce distinctive agricultural by-products and decorations such as blueberry drinks and cultural artwork made of birch bark.

The services provided by these forests have direct links with the UN´s Sustainable Development Goals. In this region, forests play an important role in air purification, noise reduction, greenhouse gas absorbance, climate regulation, soil and water loss control, and flood disaster reduction, thus greatly improving people’s living standards (Zhang 2007). Forests are an important foundation for developing the economy and improving people’s lives. As in any other region around the world, forests can provide the wood, food, medicine, fuel, and industrial raw materials that people need. In fact, with the continuous improvement of people's living standards in China, the greater demand for forest tourism has increased people's enjoyment of the mental and physical pleasures of being in the forest, and this is the other source of well-being that the forest brings to humans. Such desire to share these benefits has been translated into plans to create urban forests, including urban forest parks and avenues, provides spaces for people to rest after meals or on holidays. Such spaces play a positive role in people's physical and mental health, and thus can improve their happiness.

In addition, forests in this region have a direct link with poverty reduction strategies. The forests in the Greater Khingan Mountains are mostly distributed in remote mountainous countryside, where farmers are highly dependent on forest products. The products from forests can provide nutrient-rich foods for farmers to secure their well-being. Firewood is the main source of household energy for farmers, especially impoverished farmers, and the construction of farmers' houses is largely dependent on forest products. Farmers who live on forest products can obtain household income through selling forest products such as fruits and herbal medicine. This compensates for the loss of food and income caused by a reduction in crop yields, which in turn reduces poverty. Industrial value chains with the theme of forest service functions such as forest tourism, agricultural product processing, and construction material processing can be developed to increase employment and thereby reduce poverty.

4.2 Case study: Mediterranean Forests in Southern Spain

Temperate forests occur between the subtropical zone (about 28-30º N) and the boreal zone (46-47º N), although the temperate coniferous rain forests of the Pacific coast of Canada and Alaska grow a little north of 56ºC (Hendrick 2001). The temperate domain occupies the regions where average temperatures over 10 ºC occurs from four to eight months of the year (FAO 2012). It covers a vast territory at mid latitudes, mainly on the northern hemisphere across North America and Eurasia. The domain experiment changes in the vegetation determined by continentality and altitude. Regions influenced by the mild oceanic climate are dominated by deciduous broadleaved species, being *Fagus sylvatica* the main example in Western Europe (San-Miguel-Ayanz 2016). Mixed forests are common, even intermingling with conifers, which can become dominant as in the case of *Pseudotsuga menziesii* and *Thuja plicata* in the western part of North America. Although there are changes in the identity of the dominant species, mixed broadleaved and conifer species keep their importance while increasing the region continentality. Finally, in colder climates broadleaved species concede importance to conifers and, for example, species from the genus *Pinus*, *Abies*, *Tsuga* or *Picea* tend to dominate in the temperate mountains. To the interior of the continents, the forest transforms first into a steppe and then into a desert as in the case of the Gobi desert (Simons et al. 2001).

Mediterranean forests are a special case of temperate forests, characterized by having a dry and hot summer and a mild and wet winter, which translates into plants being adapted more to resist drought and fire that to resist frost (Grebner et al. 2013). The Spanish southern region of Andalusia encompasses is a typical Mediterranean region (Fig. 5). With a great variety in orography, climate, soil types and history of human management, added to Andalusia´s position at the southwestern end of Europe and only a few dozens of kilometers from Africa, Andalusia has a rich and biodiverse forest composition, which translates into many areas of special natural interest. Oak species are dominant, mainly holm oak (*Quercus ilex*) and cork oak (*Q. suber*), counting for 22% of forest areas. However, more than half (57%) of the non-agricultural lands are tree-less shrublands. As in the rest of the temperate zone, present forest distribution is strongly dependent of the historical human activity, which in the case of temperate woodlands usually meant alternating periods of deforestation and regeneration depending on economic needs (e.g. Verheyen et al. 1999). Forest area have been often altered by the conversion into cropland or pastures, while timber extraction has been the main ecosystem service associated to temperate forests. However, they are being increasingly valued not only for the wood production but also for the broad range of ecosystem services they can offer. In fact, the higher demand in forest products and services is considered the cause behind the recent rise in temperate forest area, and sustainable management that allow forest exploitation without compromising those ecosystem services, is being recognized as a key in the future of forests (FAO 2016). For example, in the case of Andalusia, foresters have extensively planted several species of pine and eucalyptus during the last century. In addition, Andalusia has a typical human-made savanna-like formation called “dehesa”, in which the herbaceous layer that separates trees is grazed by different livestock species (Anaya-Romero et al. 2016). The Andalusian forests provide at least 22 ecosystem services (Table 1). Among the set of ecosystem services, some are fundamental in the face of global change.

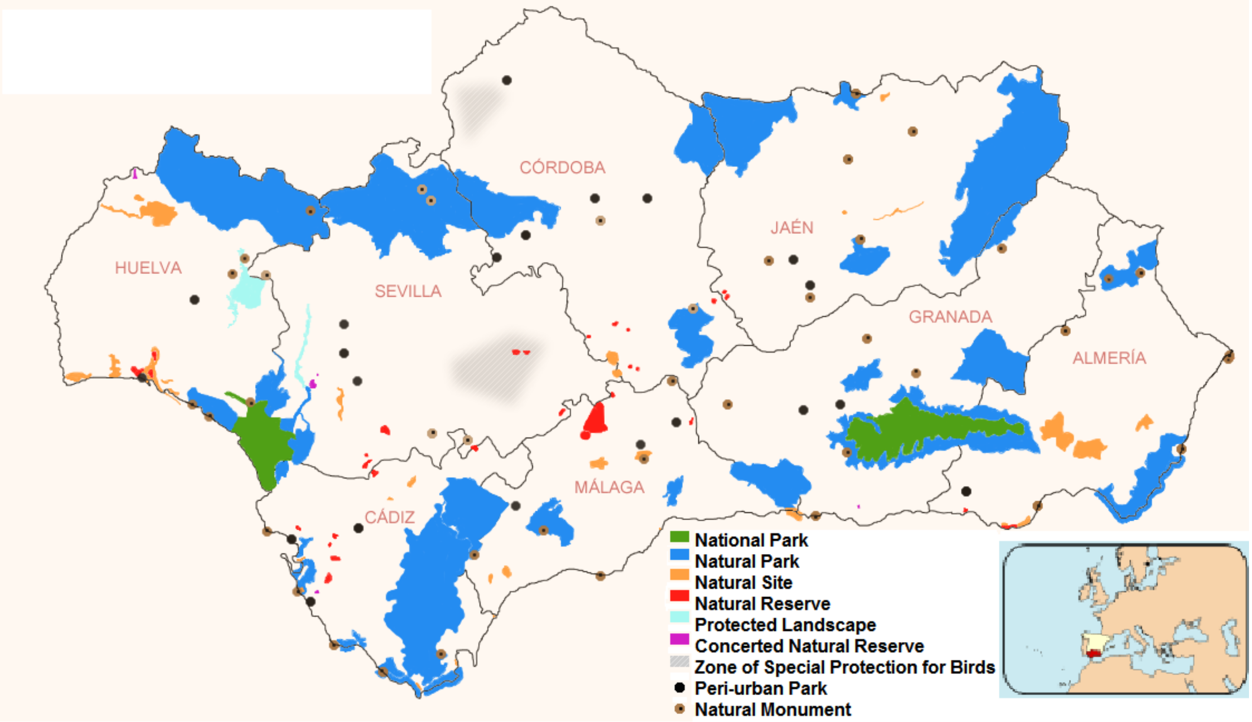

Fig. 5. Location of natural reserves in Andalusia (southern Spain), mostly encompassing forested areas in mountains, except in coastal areas (own elaboration).

Temperate forests are involved in important functions maintaining ecological cycles such as water and carbon. Slowing superficial water flow, and thus favoring infiltration this ecosystems improve water conservation, and they can act as sinks for global carbon mitigating the impact of global warming. At global scale, as the temperate forest area increased, its sink capacity also rose contributing up to a third of the global C sinks between 2000 and 2007 (Pan et al. 2011). In Andalusia, C pools in trees have greatly increased over the last half century through a process of afforestation (changing from agricultural and semi-natural areas to forests), which has consisted in planting mostly Mediterranean pine species (*Pinus halepensis*, *P. pinaster*, *P. nigra*, *P. pinea*) (Fig. 6).

Fig. 6. Typical forest landscape in Andalusia, a mixture of natural, afforested and managed forests (reproduced with permission).

Table 1. Ecosystem services (ES) provided by Andalusian forests. Indicating their relative importance and the trend over the last decades (adapted from Marañón et al. 2012).

Type of ES	**Ecosystem Service**	**Importance**	**Trend**
Provisioning	Foods (traditional)	High	Mixed
	Fresh water	High	Increasing
	Raw materials (biological)	High	Increasing
	Raw materials (mineral)	Low	Mixed
	Renewable energy	Medium-high	Increasing
	Genetic diversity	High	Decreasing
	Medicinal resources	Medium-low	Decreasing
Regulating	Climatic	High	Highly increasing
	Air quality	Medium-high	Increasing
	Water regulation	High	Mixed
	Sedimentary regulation	High	Mixed
	Soil formation and fertility	High	Increasing
	Regulation of natural disturbances	Medium-high	Mixed
	Bilogical control	Medium-low	Mixed
	Pollination	Medium-low	Decreasing
Cultural	Scientific knowledge	Medium-high	Highly increasing
	Local ecological knowledge	Medium-high	Decreasing
	Cultural identity and sense of belonging	Medium-low	Decreasing
	Cultural and spiritual enjoyment	Medium-low	Increasing
	Landscape and aesthetic appreciation	High	Mixed
	Recreation and ecotourism	High	Highly increasing
	Environmental education	High	Increasing

Other important services are soil protection from erosion, conservation of natural resources such as biodiversity or non-wood forest products, and cultural and recreational values. Timber extraction shows trade-offs with these other services, as it often implies loss of forest area and complexity (e.g. Galicia and Zarco-Arista 2014), thus the need of monitoring different ecosystem services and not only logging capacity or cork production in order to achieve a sustainable management.

Direct drivers of change are mainly two: land use change processes and climate change. Although forests in general have faced overexploitation as a main threat and their area has decreased, in the case of temperate forests, the trend has been inverted and their area has expanded in the last decades (Keenan et al. 2015). For example, during the last half century forests in Andalusia have been able to maintain a relative degree of conservation, still occupying 88% of the forested areas they covered in the 1950s. As in all European temperate areas, and more prominently in Mediterranean areas, land use change over the last half century has consisted mostly in abandonment of mountain pastures and crops, and to a lesser degree in creation of infrastructures (i.e. water reservoirs, highways, train tracks), as well as urban expansion.

Other direct drivers for change increasingly important in Andalusia and other Mediterranean regions: habitat fragmentation and fires, both interacting negatively with climate change (Valladares et al. 2014). Thus, the ability of populations to adapt to changing conditions is diminished in fragmented patches because of reduced genetic variation and dispersal capacity, making species more vulnerable to warming. On the other hand, synergies among land abandonment which promotes the build-up of wood-fuel, afforestation of old fields with conifers and eucalypts, increasing efforts in fire suppression, and increase in human population have led to increase of fires size and frequency (Valladares et al. 2014). Increases in both the length of the fire seasons and the frequency of extreme heatwaves will contribute to exacerbate these synergies.

Another direct driver for change is the increasing presence of invasive species, which are becoming a hazard of increasing importance as human trade facilitates their displacement (Leung et al. 2012). In the long-term, invasive species cause a reduction of biodiversity, as several local species are displaced by a few invasive species. Invasive species have usually more impact on monocultures and even-aged stands than on mixed uneven-age stands (Guyot et al. 2015). Mixing tree species also increase the potential of the forest as biodiversity reservoir due to the different biota associated with each species (Cavard et al. 2011) and, in this manner, ecosystem services are also influenced by tree diversity. Total forest productivity can be also improved by mixing species, for example, by means of increasing structural heterogeneity (Pretzsch 2014) or improving the system resilience against hazards (Griess and Knoke 2011, Griess et al. 2012). For these reason, there is a trend in European temperate forests to increase the importance of mixed stands and reduce the presence of monocultures, usually by not removing naturally regenerated broadleaves in coniferous-dominated stands (Felton et al. 2016).

Climate change is creating stressors that weaken trees. While independent stressors usually cause minor cases of tree mortality, defoliation or declines in growth, concern is being raised over extreme droughts and heat waves as they are expected to occur more often in the future. Indeed, extensive forest mortality has been found in the last years when drought and heat waves combine with additional disturbance drivers (Millar and Stephenson 2015). In Andalusia, there are already reports of diebacks, reduced growth and high potential for range distribution ranges of the main tree species (Navarro-Cerrillo et al. 2018)

Country policies can also be indirect drivers of change, for example, creating new biodiversity conservation areas where logging activities or forest conversion are limited (Fig. 5). Another case is the promotion of renewable energies. Woodland biomass utilization for energy is often not profitable when competing with modern fuels prices, but new policies promoting renewable energies could favor its use where the wood industry is well developed, as could be the case of California (Nicholls et al. 2018) which also has a Mediterranean climate. Repopulation of rural areas in North America or Europe could potentially increase the use of firewood. As wood is very voluminous in relation to the heat produced, the transport is considerably more expensive than for other fuel options, so reducing the distance between the forest and the population would change the balance between fuel prices in favor of wood biomass. This could be the case of Andalusia, for which great potential but also great barriers to act as an energy source has been identified (Ovando 2017).

In Andalusia, cork prices and trends can have consequences of the extension and management of cork oak (Marañón et al. 2012). As natural cork is being substituted in some countries by plastic bottle stoppers, cork use can be reduced and therefore management abandoned, or the opposite if natural cork is used by brands as “quality touch” to improve wine bottle visual quality. Therefore, forested rural areas are benefited by forest industry given its importance as an income source relative to other activities. Therefore, promoting it could be a way of creating new employment opportunities, especially in areas affected by rural depopulation (e.g. Pašakarnis et al. 2013, Pinilla et al. 2008). However, over the last decades, employment in the global temperate forest has decreased sharply, from almost 3 million employees in 1990 to less than 2 million in 2010, which could be related to the improvement of logging techniques (FAO 2016). Such lack of employment opportunities is behind most of the reasons that convince rural dwellers to move to urban areas, causing land use change by reduction of agricultural and forestry activities.

4.3 Case study: Tropical Forest of the Ecuadorian Amazon Basin

Tropical forests occur between the Tropic of Cancer (23.5º) and the Tropic of Capricorn (23.5º S). They are located in three geographical formations: American, African and Indo-Malesian. The tropics generally correspond to frost-free areas where the mean annual temperature is 18 ºC or above or where the mean monthly temperature difference between the three warmest and three coldest months is 5ºC or less (Hendrick 2001). There are five primary forest types (Longman and Jenik 1987 in Hendrick 2001): tropical evergreen, (sub) tropical seasonal, (sub) tropical semidecidous, sub (tropical) evergreen and mangrove.

The Amazon rainforest covers an area of 7 million km^2 and is the largest rainforest on Earth, stretching over nine countries: Brazil, Colombia, Peru, Venezuela, Ecuador, Bolivia, Guyana Surinam and French Guyana (Saatchi et al. 2007). The Amazon rainforest has multiple ecosystems and types of forests in each country according to the physiognomy, phenology, general flooding, geological form, bioclimate, bioclimatic floor, substratum and biogeography (Ecuador Ministry of Environment 2013).

In Ecuador, the Amazon basin covers areas under 1300 m.a.s.l. in the eastern foothills of the Andes, including all mountain ranges and lowlands to the east of this limit (De la Torre et al. 2008). The Amazon basin also covers almost 50% of the Ecuadorian territory (Palacios et al. 1999) and contains 22 ecosystems, which include several types of forest, such as lowland evergreen rainforests, flooding forests, evergreen piedmont forest, evergreen low-montane forest, shrubs and grasslands (Ecuador Ministry of Environment 2013).

The Ecuadorian Amazon region contains two National Parks, four Biological Reserves, two Ecological Reserves, one Municipal Ecological Conservation Area, one Wildlife Reserve and one Faunistic Production Reserve. The Protected Area of our interest has recently been declared as a Biological Reserve in 2014 and it is called Colonso Chalupas (MAE 2017).

The Colonso Chalupas Biological Reserve (CCBR) is located on the east slope of the Andes, in the Napo province between the Antisana Ecological Reserve in the northeast and the Llanganates National Park in the south (Fig.7). Its surface has 93,246 ha and the altitudinal range goes from 720 to 4432 m.a.s.l (van der Hoek et al. 2018), the temperature fluctuates from 6.8 °C to 24.4 °C (INER 2015), it receives an annual precipitation about 1700 mm in the highest part and 4300 mm in the low part (Alvarez-Solas et al, 2016). The Reserve presents six different types of ecosystems:

- Northern evergreen high montane forest of the eastern Andes Cordillera (9,287.30 ha),
- Northern evergreen low montane forest of the eastern Andes Cordillera (37,960.45 ha),
- Northern evergreen montane forest of the eastern Andes Cordillera (28,747.74 ha),

- Northern evergreen piedmont forest of the eastern Andes Cordillera (5,753.28 ha),
- Paramo wild herbs (11,357.36 ha), and
- Paramo wild herbs ultra-wet subnival (46.62 ha) (MAE 2017) (Fig. 8).

The reserve is also limited by 23 indigenous Kichwa communities (Yaguache et al. 2016).

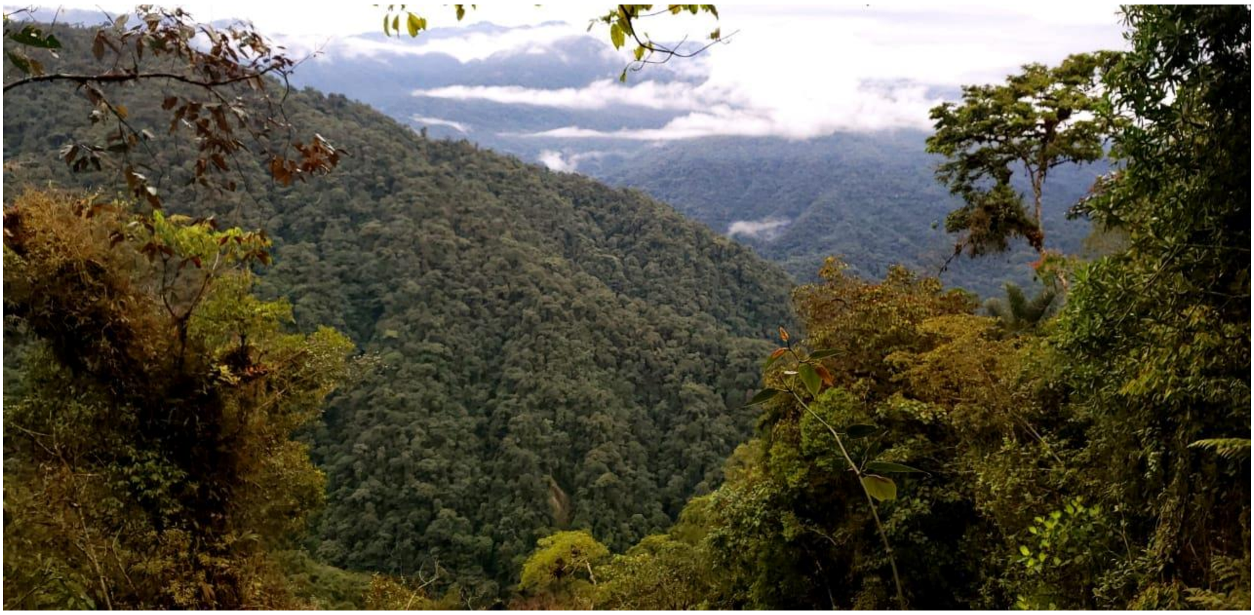

Figure 7. Biological Reserve Colonso Chalupas (Credit: Byron Maza).

The reserve harbors 167 species of birds (15 of them are migratory and 8 endemic), 10 species of amphibians, 4 species of reptiles, and 18 species of mammals. There is no data about the number of insects and other arthropods. There are 171 families of plants with 649 genera and 1841 species (MAE 2017). The levels of biodiversity and endemism are thought to be high, very similar to hotspots (van der Hoek et al. 2018). More research is needed to know the real number of animal and plant species to recognize how many ecosystem services the CCBR can provide.

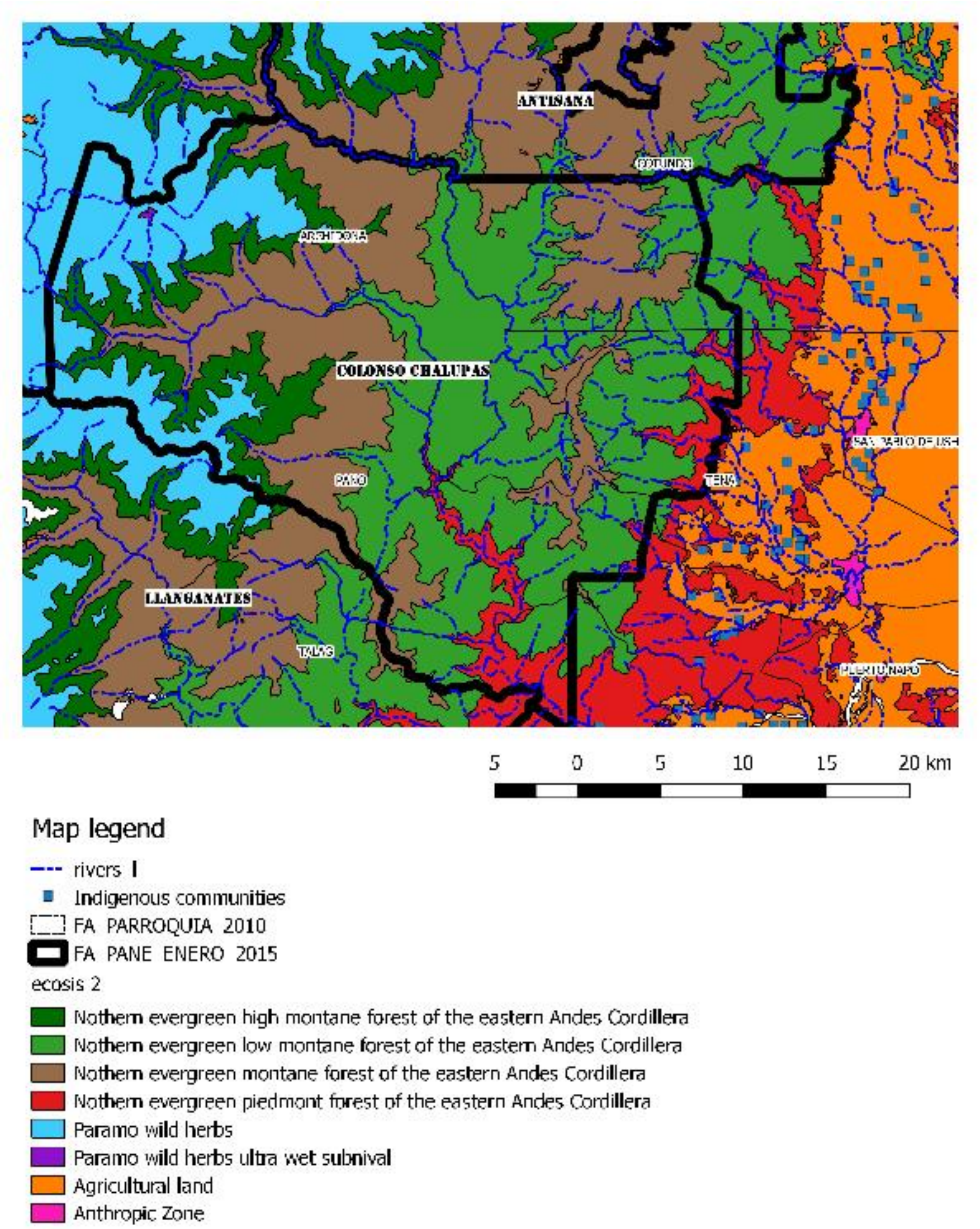

Figure 8. Colonso Chalupas Biological Reserve with their ecosystem types (own elaboration)

In the reserve, forests provide some ecosystem services that deliver direct or indirect benefits for human wellbeing (Fig. 9). These ecosystem services are:

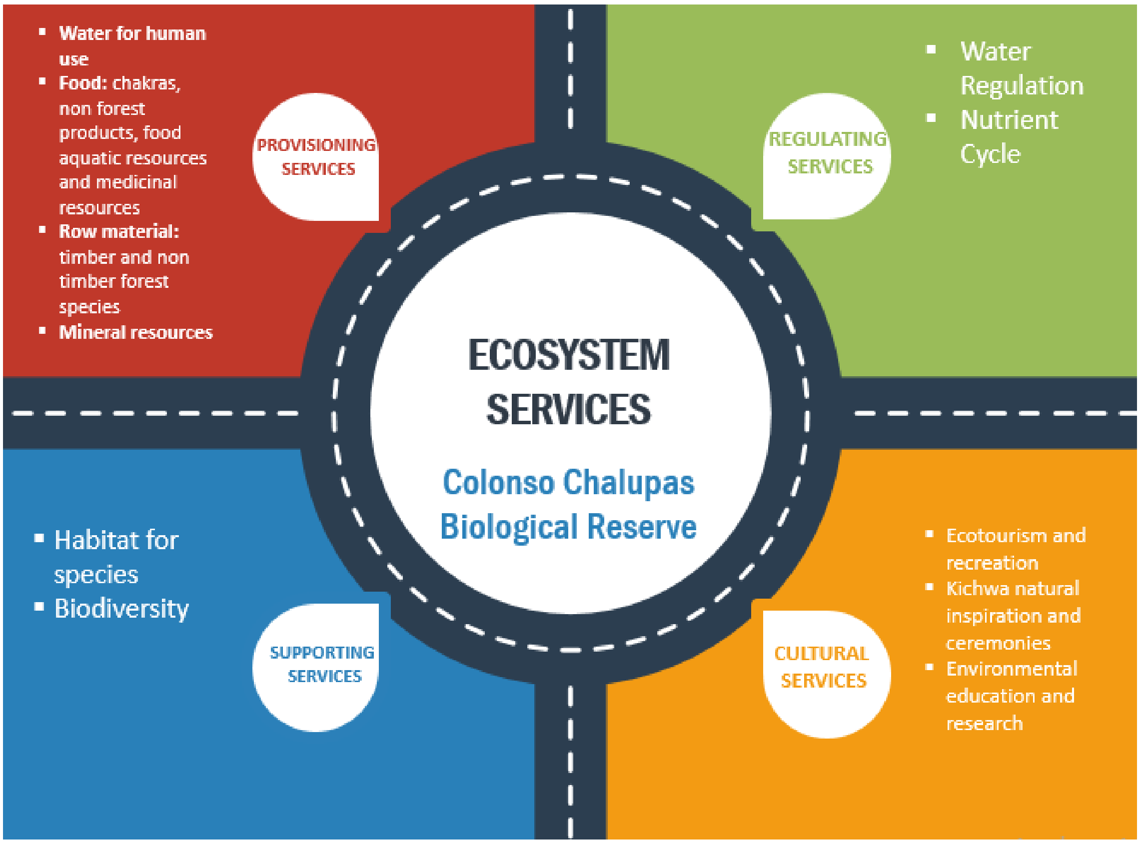

Figure 9. Ecosystem Services of Colonso Chalupas Biological Reserve (own elaboration)

1) *Provisioning services:* material and tangibles services such as food, fibers, fuel, genetic, pharmaceutical, ornamental, food aquatic and mineral resources. The people use “chakras” as an agroforestry system in which they plant their own food, timber and non-timber species. Some investigations have shown that the communities use 95 species of plants for food, commercial, medicinal and cultural uses (Peñuela-Mora et al. 2016).

2) *Regulating services*: every benefit generated as a product of ecological processes essential for the support of the agroecosystem such as: protection against natural disasters (being floods the most typical and potentially damaging in this region), stabilization of climate and air, fertility and control of soil erosion, biological control of diseases and species, pollination, purification and stability of water sources and nutrient cycle (MAE 2017).

3) *Cultural services:* It is common that kichwa communities use nature as inspiration for legends, and myths, so too they use their dreams to predict their future (Mendoza Orellana 2012). In addition, there are different cultural events around nature such as Jandia warmi and Guayusa warmi that highlight women in the community. There are a strongly linked to values and human behavior, and determine the behavioral patterns, social institutions and organization political and economic society (Molina 2018).

4) *Supporting services*: Support services refer to the ecological processes that ensure the proper functioning of natural systems, such as biodiversity and habitat (Villamagna and Giesecke 2014). CCBR is habitat for many threat species such as cougar (*Puma concolor*), chorongo monkey (*Lagothrix lagothricha poeppigii*), peccary (*Pecari tajacu*), chuncho tree (*Cedrelinga Cateniformes*), canelo tree (*Ocotea javitensis*), copal tree (*Dacryodes cupularis*) and Ungurahua palm (*Oenocarpus bataua),* a keystone specie as a food source for a great diversity of birds and mammals (MAE-GIZ-IKIAM 2017). This ecosystem service differ to the extent that there is no direct use of these services, however, the impacts on the stability of these services indirectly affect society during long periods of time (UK NEA 2011).

The forests at the CCBR are under different drivers of change (Fig. 10). Drivers, natural or anthropogenic, directly and indirectly affect the ecosystem services. Natural drivers include disasters such as earthquakes and volcanic eruptions linked to the geological and tectonic activity in the Andean cordillera. In addition, extreme weather related events such as prolonged drought are usually directly related to El Niño/La Niña (ENSO) phenomenon (Bustamente *et al.,* 2018). The direct anthropogenic drivers, which are modulated by indirect drivers (e.g., natural resources demand) are the outcome of human activities and governance decisions (Bustamente *et al.*, 2018) that influence the ecosystem processes.

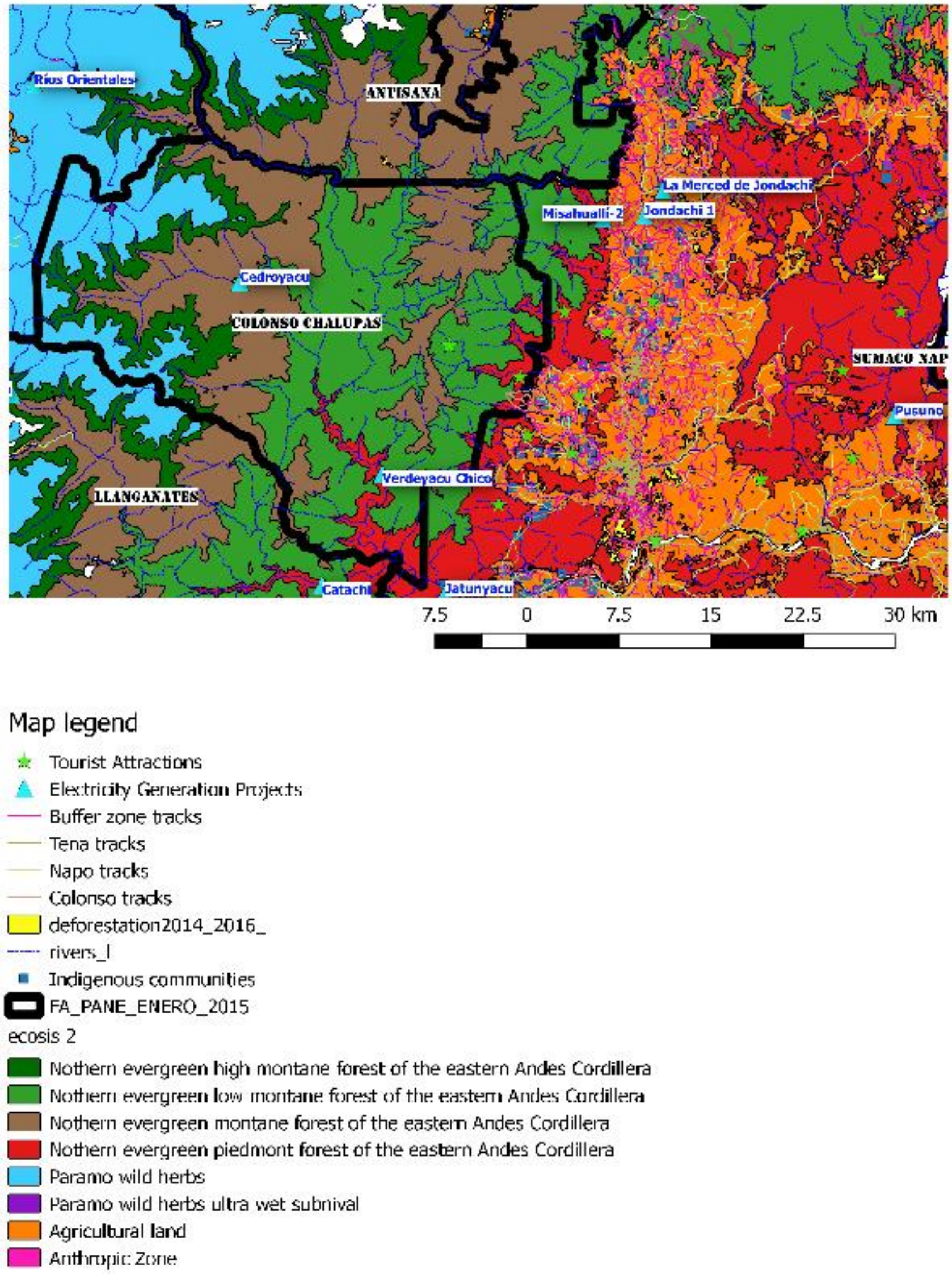

Figure 10. Direct drivers of change in Colonso Chalupas Biological Reserve (own elaboration).

It is well known that climate change is affecting the Amazon rainforest and is one of the anthropogenic drivers of ecosystem change. In particular, drought events in association with forest fragmentation and anthropogenic ignition sources are already causing widespread fire-induced tree mortality and forest degradation across the southeastern Amazon (Brando et al. 2014). Climate model scenarios indicate a constant warming in the 21st century for the tropical troposphere, with a temperature increase at higher elevations. Is expected that for the end of 21st century an increase of 4.5-5◦C will occur in the tropical Andes, with stronger wet and dry seasons (Vuille et al. 2008). During the last years, anomalies in the beginning and the end of rainy seasons, increasing the precipitation intensity and the maximum temperatures of the day have been already reported in the Napo province (Gobierno Autónomo Descentralizado Provincial del Napo 2015).

As consequence of these climate change scenarios for the Colonso Chalupas Biological Reserve, the main direct drivers of change are droughts that will alter the water sources and vegetation in paramo, forest fires in the highlands of the reserve as consequence of drought and human activities, floodings in the lowlands of the reserve in rainy seasons by the increase of river flow. In turn, these floodings could generate mass soil movements such as landslides that could affect locally but massively the vegetation and fauna of the reserve (MAE-GIZ-IKIAM 2017).

Over-exploitation of the Amazon basin in the 20th century has generated population decreases of iconic vertebrate species (both predators and game species). The ecological consequences of such defaunation already threat the food security of local communities because bushmeat has a fundamental role as protein source for the local dwellers (Campos-Silva et al. 2017). In addition to over-exploitation of timber and palms by logging (illegal or legal), mineral resources exploration and extraction, cropping intensification of Amazon species (guayusa *Ilex guayusa* Loes., cocoa *Theobroma cacao* L.), energy production and aquatic resources are some examples of drivers of change that has experienced the Ecuadorian Amazon (MAE-GIZ-IKIAM 2017) (Fig. 10).

The over-exploitation in the last years of timber species such as chuncho (*Cedrelinga cateniformis*), Canelo (*Ocotea javitensis*) and Copal (*Dacryodes cupularis*) and non-timber forest species such as the ungurahua palm (*Oenocarpus bataua*) has decreased the population of these species in the reserve and in the buffer zone. The decrease of these populations has already produced ecological outcomes (MAE-GIZ-IKIAM, 2017) (Figs. 11 to 14).

Habitat change in these tropical forests is evident by agriculture, land use change and road building cause evident habitat changes in these tropical forests. These drivers are threatening all ecosystem services and biodiversity. The main driver of habitat change in the buffer zone of Colonso Chalupas Biological Reserve is agriculture, because most of the local communities use the traditional agroforestry system (chakras) for self-consumption or for selling their crops in local markets. However, crop intensification is a current phenomenon in Napo province because there are international companies buying cocoa and guayusa tea to local communities for chocolate and tea exportation. In addition, this agroforestry system is used as a focus for agro-tourism activities (MAE-GIZ-IKIAM 2017).

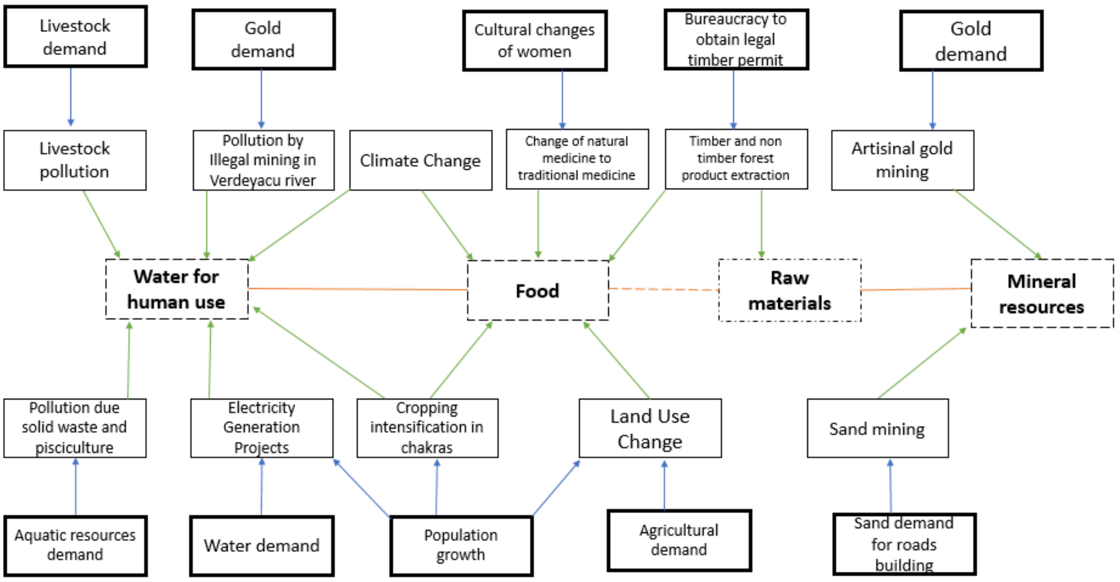

Figure 11. Direct and indirect drivers of change for *Provisioning Ecosystem Service* in Colonso Chalupas Biological Reserve (MAE-GIZ-IKIAM, 2017). Indirect drivers in bold (own ellaboration)

The main introduced species in the Ecuadorian Amazon are the foreign plants used in agroforestry systems, unfortunately some of them are naturalized (e.g. banana – *Musa sp.).* In addition, the animals used for cattle and for human support are considered introduced species too. Although in the Colonso Chalupas Biological Reserve there are not invasive species registered yet, in the buffer zone of the reserve small tilapia fish (*Oreochromis* sp.) pools are already affecting the habitat, and native and endemic fishes of rivers (MAE-GIZ-IKIAM 2017).

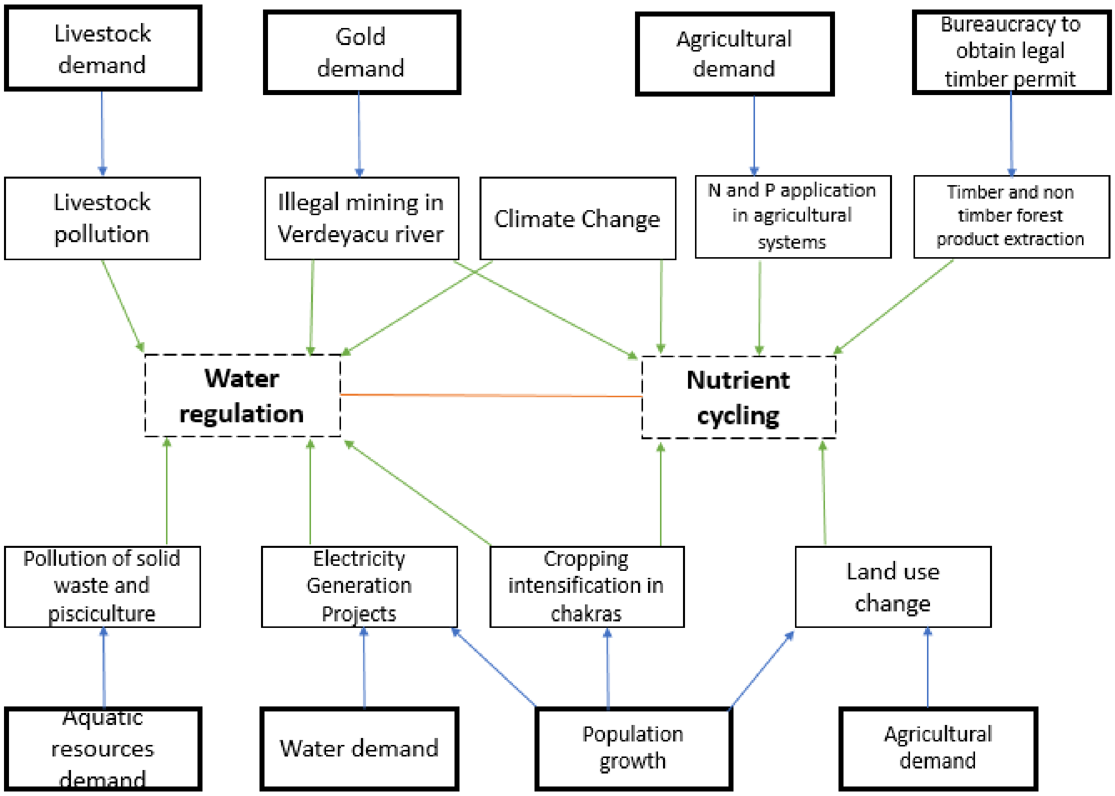

Figure 12. Direct and indirect drivers of change for *Regulating Ecosystem Service* in Colonso Chalupas Biological Reserve (MAE-GIZ-IKIAM, 2017). Indirect drivers in bold (own ellaboration)

Pollution is one of the main direct drivers that affect all ecosystem services through different activities. Although in the protected area, activities that generate pollution are not allowed, it is known that there is pollution due to illegal mining in the Verdeyacu River located inside the reserve. In the highlands, there is also pollution due to livestock activity. In addition, the infrastructure and buildings for touristic and research/academic activities are a threat to the piedmont forest located in the buffer zone (Figs. 8-11) (MAE-GIZ-IKIAM 2017). In addition, in the buffer zone of the reserve the river is polluted by fish farming of tilapia (invasive fish) and cachama (a local Amazonian fish, *Colossoma macropomum*) (Yaguache et al. 2016).

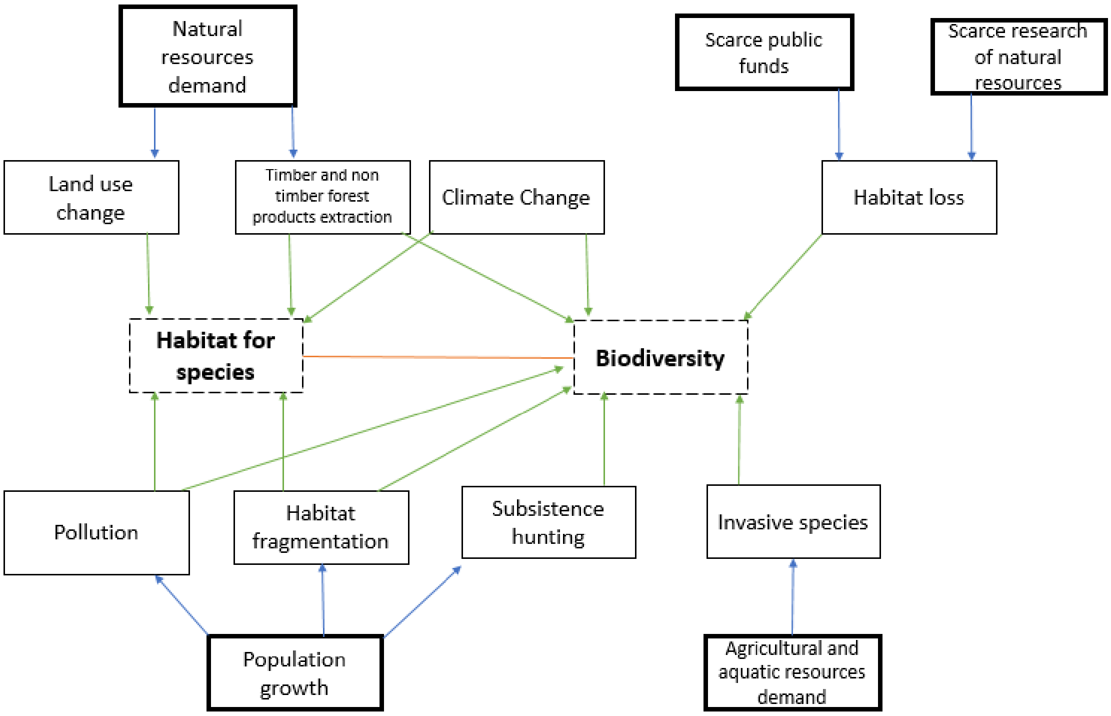

Figure 13. Direct and indirect drivers of change for *Supporting Ecosystem Service* in Colonso Chalupas Biological Reserve (MAE-GIZ-IKIAM, 2017). Indirect drivers in bold (own elaboration)

Most of the direct drivers are affected by indirect drivers. The main indirect drivers for the Colonso Chalupas Biological Reserve are the changes in natural resources demand by local populations, which in the buffer zone include the agriculture and timber/non timber forest product extraction, tourism and research demand, sand demand for roads building, aquatic resources demand (tilapia and cachama fishes) (Figs. 11 to 14). Inside the reserve, the main indirect drivers are human demand for water, energy, minerals and livestock. All of these indirect drivers are the result of population growth: from 1962 to 2001 the urban and rural population has increased in the Napo province by 7.5% and 32.5% respectively (Instituto Nacional de Estadísticas y Censos 2002). In addition, 78.6% of the people in the Napo province are considered as living under the poverty threshold due to the lack of unsatisfied basic needs (Instituto Nacional de Estadísticas y Censos 2010). Most of the communities located in the buffer zone of the Colonso Chalupas Reserve are indigenous (from the Kichwa ethnic group), whose youngest generation, through the globalization process, are modifying their language and historical traditions on natural resource uses and demands (MAE-GIZ-IKIAM 2017).

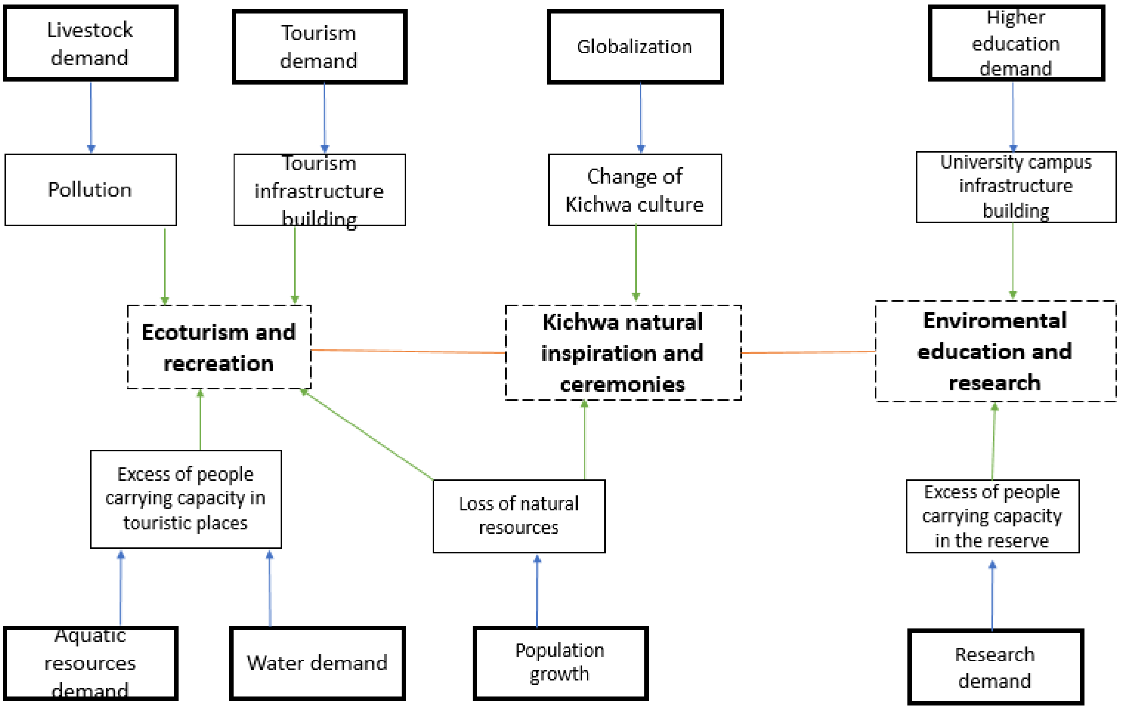

Figure 14. Direct and indirect drivers of change for *Cultural Ecosystem Service* in Colonso Chalupas Biological Reserve (MAE-GIZ-IKIAM, 2017). Indirect drivers in bold (own ellaboration)

(own elaboration)

Some national policies are also indirect drivers that affect all ecosystem services in the reserve. On the other hand, the scarce public funds for maintaining and overseeing the reserve do not allow a full real-time surveillance, and in addition, the bureaucracy to access timber permits promotes illegal timber extraction (MAE-GIZ-IKIAM 2017).

In this context, all the ecosystem services of Colonso Chalupas Biological Reserve and the ecosystem services from the Amazon basin support one of several of the UN´s Sustainable Development Goals for 2030. Although direct and indirect drivers affect these ecosystem services, the communities located in the buffer zone benefit and depend on these natural resources. Finally as the buffer zone of the reserve has different pressures like direct and indirect drivers, there are national initiatives such as ProAmazonía that pretend to reduce these drivers with bio-enterprises using local products and initiatives such as “SocioBosque” that pretends to conserve long term native forest through the use of economic incentives.

5. Concluding Remarks

- Forest ecosystems are key actors to reach many of UN´s Sustainable Development Goals, given the number and importance of ecosystem services they provide.
- Relative to other terrestrial ecosystems, forests have low surface albedo, high carbon storage capacity, high CO_2 uptake and high evapotranspiration rates, which allow them to modulate climate (i.e., regulating services). In addition, they can also provide characteristic provisioning, supporting and cultural services.
- The importance of these services varies between boreal, temperate and tropical forest. For instance, climate control and biodiversity are highest in tropical forests and lowest in boreal forests.
- All these forest biomes are threatened by logging, fire, fragmentation, inadequate management, pest and disease outbreaks and air pollution. These disturbances are interacting with climate and land use changes, resulting in synergies that are generating “a new normal” based on complexity and dynamic stability, which makes difficult predicting ecosystem attributes and services.
- Global trends attributable to climate change include latitudinal and altitudinal range shifts, phenological advances and delays in growth or reproduction, and changes in disturbance patterns (i.e., tree pest and diseases, fire and drought) resulting in alterations in community structure and function.
- Climate change is also influencing productivity, species interactions and nutrient cycling of forest ecosystems, all of which interact among them in a complex way. These interactions appear to be different in boreal, temperate and tropical forests. Therefore more research is needed to understand how climate factors affect different aspects of forest functioning and structure in order to predict forest responses on ecosystem services provided by forests.
- Evidence is mounting about the existence of positive relationship between biodiversity and forest function (i.e., regulating services) in boreal, temperate and tropical forests. However, climate change through changes in water availability appears to modulate the strength of the relationship at least in boreal and Mediterranean forests.
- Knowledge of synergies between different ecosystem services is needed to assure sustainable forest management. For instance, transforming monocultures into mixed forests appears to be a good compromise to increase productivity (i.e., timber, pulp) and mitigate climate change through increases in CO_2 absorption. In this context, an integrated production system for wood and bioenergy exhibits an example of synergy as thinned stands maximize the value of wood products, while thinnings are used for bioenergy.

- Understanding synergies among non-timber forest products, climate and land use changes and other drivers appears to be crucial in tropical forests, where millions of people live below the thresholds of poverty and depend on forests for food provisioning.
- Forests play a major role in regulating water flows (quantity, quality and seasonality) in areas where climate change exacerbates water scarcity and threatens food security.
- Assessment of ecosystem services by means of theoretical models taking into account species´ functional traits rather than only ecosystem processes seems promising.
- Difficulty in predicting impacts of climate change on ecosystem function and consequently on ecosystem services is mainly caused by the site-specific nature of many of these ecosystems services, and particularly cultural, recreational and spiritual services that depend not only on the forests but also on the people living in the region or with access to those forests.
- The case studies presented as representative examples of good health and well-being in boreal, temperate and tropical forest illustrate how the relationships of humans with forests, which are dynamic and complex, are strongly influenced by the ecological-socioeconomic background and the drivers of change. Despite of this, common patterns and processes emerge which are the base, as many studies are showing, to improve human well-being.
- Indirect drivers such as social, economic and political trends can have important influences on forest ecosystems, and therefore sustainable forest planning to support UN´s SDGs must be linked to other planning activities at local, regional, national and international levels.

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