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Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study

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ABSTRACT

If the world stays on its current development path, the state of biodiversity will continue to decline. This is due to projected further increases in pressures, most prominently habitat loss and climate change. In order to reduce these pressures, biodiversity conservation and restoration, as well as sustainable resource use, needs to be an integral part of sustainable development strategies of primary production sectors, such as agriculture, forestry, fisheries and energy. This paper presents a model-based analysis of three alternative pathways described as *Global Technology*, *Decentralized Solutions* and *Consumption Change* to conserve biodiversity. Each of these pathways pursues international biodiversity goals together with a broader set of environmental sustainability objectives, including feeding the world, universal access to modern energy, limiting climate change and controlling air pollution. We show that different combinations of bio-physical measures, ecosystem management changes and behavioural changes can globally substantially reduce biodiversity loss in the coming decades (avoided Mean Species Abundance (MSA) loss is 4.4–4.8% MSA, compared to 9.5% MSA loss in the Trend), although the types of biodiversity conserved in the pathways will be different. The agricultural and forestry sectors together have until 2010 globally caused almost 60% of the total reduction in terrestrial biodiversity in MSA terms and 55% of the expected loss up to 2050. We show that increased productivity by technological improvements, increased use of ecological methods in agriculture and forestry, and consumption changes help to avoid biodiversity loss by 3.1–3.5% MSA. In addition, combinations of pathways, taking into account specific regional contexts, might result in even larger reduction of biodiversity loss. The changes needed in the agricultural and forestry sector to achieve this go well beyond current efforts to reduce their impact on biodiversity.

1. Introduction

The mid-term evaluation of progress towards the attainment of the 2020 Aichi Biodiversity Targets set in the United Nations Convention on Biological Diversity (CBD) shows that, if the world stays on its current development path, the state of biodiversity will continue to decline. While there has been an increase in the societal responses to biodiversity loss, in most cases this will not be sufficient to achieve the biodiversity targets by 2020, let alone to realise the long-term vision of the CBD (Leadley et al., 2014, sCBD, 2014, Tittensor et al., 2014). The latter is formulated as ‘by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people’ (CBD, 2010).

Analyses have shown that the fate of the world's biodiversity will largely be shaped by activities in the agriculture, fisheries, extraction industries, energy production, water management, and forestry sectors. These sectors exert direct pressures on biodiversity such as land use change, pollution and climate change (Donald et al., 2002; Green et al., 2005; MA, 2005; sCBD, 2014; Spangenberg, 2007; Ten Brink et al., 2010). If current trends continue, the global demand for food, wood, water and energy is projected to increase 1.5–2 fold by 2050 as

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compared to 2010 as a consequence of the expected rise in global population and increasing wealth (OECD, 2012; Riahi et al., 2017; van Vuuren et al., 2015). This paper evaluates the impacts on biodiversity of different response strategies in the agriculture and forestry sectors, all of which aim at achieving similar outcomes for a range of sustainability objectives by 2050.

Often, scenarios are designed to explore how the future could evolve on the basis of pre-set storylines - a set of assumptions - also referred to as explorative scenarios (IPBES, 2016; van Vuuren et al., 2012b). In contrast, in the current analysis we apply scenarios that meet a range of long-term environmental sustainability objectives, including those for biodiversity, and analyse diverse response strategies for the agricultural and forestry sectors to achieve those objectives. This approach, known as back-casting (Dreborg, 1996; Robinson, 1982) or target seeking scenarios (IPBES, 2016), explores how different trajectories towards specific objectives may look and is used to identify short and medium-term priorities and efforts required to achieve long-term goals. The trajectories analysed are referred to as "pathways" in this paper. In the context of global scenario studies for biodiversity this approach has seldom been applied, with notable exceptions of Erb et al. (2016) who explore the biophysical option space for feeding the world without deforestation and Smith et al. (2013a) exploring how much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals including biodiversity.

The three pathways analysed in this study were originally designed to meet a broad set of environment related sustainable development objectives and include a Global Technology pathways, a Decentralized Solutions pathway and a Consumption Change pathway. They are described in (van Vuuren et al., 2012a; van Vuuren et al., 2015). Apart from achieving the 2050 vision on biodiversity, the pathways limit greenhouse gas emissions to avoid climate change beyond 2° increase by 2100; eradicate hunger by 2050; and provide universal access to safe drinking water, improved sanitation and modern energy. These objectives are in line with the Sustainable Development Goals (SDGs) that were agreed upon by all countries within the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development (UN, 2009). The pathways are quantitatively analysed using the Integrated Model for the Assessment of the Global Environment, IMAGE (Stehfest et al., 2014) combined with the Global Biodiversity model, GLOBIO (Alkemade et al., 2009; Schipper et al., 2016). The analysis is performed at global level and at the level of large world regions, with a time horizon of 2050.

The pathways were further elaborated to make them more relevant from a biodiversity and agricultural and forestry sector perspective (Kok et al., 2014). The reduction and eventual halting of biodiversity loss as is required to achieve the 2050 biodiversity vision under the CBD, is explored using distinct combinations of technological improvements of production, ecological solutions, land use management options, and consumption changes and waste reduction. These options are levers for sectors to contribute to the reduction of biodiversity loss. The Global Technology pathway emphasizes the potential of technologically advanced, sustainable intensification in agriculture potentially leading to land sparing (see for example Balmford et al., 2005; Ewers et al., 2009; Garnett et al., 2013; Green et al., 2005; Phalan et al., 2011; Tilman et al., 2011). The Decentralized Solutions pathway shows the potential for ecological innovation in mixed land use systems where natural elements are interwoven within production landscapes, potentially leading to land sharing (see for example Hulme et al., 2013; Perfecto and Vandermeer, 2010; Pywell et al., 2015; Tittonell, 2014; Tscharntke et al., 2012; van Noordwijk and Brussaard, 2014). The Consumption Change pathway highlights the potential of lower demand for food and wood products by waste reduction, efficiency improvements and of changing diets (see for example Bajzelj et al., 2014; Erb et al., 2016; Machovina et al., 2015; Parfitt et al., 2010; Stehfest et al., 2009). In all pathways, we assume extensive climate change mitigation measures and pollution is expected to be reduced. Also some other options are included in all three pathways (without further differentiation) that contribute to the realisation of the biodiversity goals, but are primarily inspired by other concerns. These are an accelerated phase-out of traditional bioenergy and simultaneously improvement of access to modern energy (to reduce indoor air pollution).

Together, the three pathways indicate an "option space" to meet biodiversity and environment related sustainable development objectives. They are used here to further explore the potential of agriculture and forestry sectors to reduce their impacts on biodiversity. We restrict ourselves here to an analysis of the potentials of options and pathways to achieve these objectives, without entering into the fundamental question of how such pathways could be realised from a political and institutional perspective. In our analysis, we also do not focus on the potential feedback of the pathways on the economy and demography. These can be important to assess investments and costs and benefits, but are also not necessary for assessing the bio-physical option-space. Furthermore we did not assess the likelihood of realisation of these pathways. It is however clear that the three pathways assume different societal preferences and governance systems between each other and all will be fundamentally different from the Trend. It goes beyond the scope of this paper to delve into that deeper (see for further analysis of these questions Kok et al. (2014)). Synergies and trade-offs among options and targets are briefly explored. This is of particular importance when, for example, climate objectives are met by increasing the share in biofuels with possible detrimental impacts on food production and biodiversity. The "option space" will differ between world regions, as priorities, context and synergies and trade-offs between options vary between regions. The pathways were also analysed for impacts on aquatic biodiversity (see for this Boelee et al., 2017). They also include an analysis of the potentials to overcome water challenges through nature based solutions.

2. Material and methods

2.1. Defining biodiversity objectives as end-points

A back-casting or target-seeking analysis first of all requires the identification of end-points to be met by the pathways. The end-points are in our case a set of environment related sustainable development objectives for 2030–2050, including the 2050 Biodiversity Vision, described in van Vuuren et al. (2015). The quantitative end-point to operationalise the long-term objective for biodiversity was derived from the Aichi Biodiversity Target 5 to 'at least halving or when feasible bringing close to zero biodiversity loss by 2020' and Target 11 'Expanding protected areas to at least 17% of terrestrial area and inland waters by 2020'. Following the intentions of the Aichi targets it is assumed that developed countries halt biodiversity loss by 2020 and developing countries from 2030 onwards, allowing developing countries some more time to meet this target, while also meeting the targets for protected areas in 2020 (CBD, 2010). Based on this, the end-point for biodiversity was calculated and by comparing the Trend with this endpoint the policy challenge was identified and expressed as avoided biodiversity loss to be realised by 2050.

2.2. Trend scenario

The so-called *Trend* scenario shows developments without new policies being introduced to achieve biodiversity or other environmental related sustainable development objectives. The Trend scenario serves as a benchmark to understand the context and challenges to achieve the biodiversity goals in the sectors and is based on the OECD Environmental Outlook for 2050 (OECD, 2012). This scenario represents an intermediate "business as usual" scenario, and has been thoroughly analysed and described, and therefore suits well for comparison with the pathways. As the focus of our analysis is on the pathways, only one baseline is used (and so we do analyse the pathways

Table 1
Main global characteristics of the Trend scenario (OECD (2012)) and its implications for natural resource use between 2010 and 2050 assuming no new policies (Kok et al. (2014) and van Vuuren et al. (2012a, 2015)).

	2010	2050	Change (%)
Population	7.0 billion	9.2 billion	+31
GDP (in 2005 prices)	67 trillion US$	257 trillion US$	+283
Global food and feed consumption	3.9 billion tonne/year	6.4 billion tonne/year	+64
Wood consumption per year (roundwood equivalent)	2.4 billion m^3	3.2 billion m^3	+33
Agricultural land (cropland and cultivated pastures)	14.3 million km^2	18.5 million km^2	+29
Total forested area	38.7 million km^2	39.2 million km^2	+1
Primary forest area	31.5 million km^2	27.9 million km^2	−11
Area of forest managed for wood production	7.1 million km^2	11.3 million km^2	+59
Area of planted forests for wood production	1.0 million km^2	1.3 million km^2	+30
Energy use	516 EJ	972 EJ	+88
Fresh water use	3212 km^3 (2000)	5642 km^3	+76

against a range of trend scenarios). This scenario assumes that world population continues to grow from around 7 billion people in 2010 to over 9 billion by 2050 (UN, 2009). This growth mostly occurs in Sub-Saharan Africa and South Asia. In all world regions a further increase in per-capita GDP is projected, with the highest growth in developing countries. As a consequence the Trend scenario shows an increase in use of natural resources and of pressures on the environment (see Table 1).

The expected increase of world food consumption to feed a growing and increasingly wealthy population requires increased production of food, crops and animal feed. The share of basic staple foods is expected to decrease, while the share of animal products in diets increases in line with historical trends. In the Trend scenario intensively used agricultural land expands by some 4 million km^2 between 2010 and 2050.

Increase in the average agricultural productivity is projected to continue at current rates of about 0.6% per year on average. The increase of extent and the increased productivity supports a 70% increase in agricultural production. Agricultural productivity increase is important for limiting the loss of biodiversity through limiting the expansion of agricultural land. However, productivity increase also implies higher negative impacts on biodiversity in the more intensively-managed areas themselves due to higher inputs of capital (mechanisation), fertilizers and other chemicals, the regulation of groundwater tables and other management activities (MacDonald et al., 2000). Nitrogen (N) and phosphorus (P) emissions are expected to increase in many parts of the world as increased fertilizer use is needed to increase agricultural productivity, despite improvements in the utilisation efficiency (Lassaletta et al., 2014). Intensification may occur especially in regions where yields are currently far below their potential, as derived from prevailing climate and soil conditions. Livestock production will shift from pastoral systems requiring vast grazing areas, towards mixed and landless production systems. The latter implies that more crops will be used to feed livestock. However, the crop areas required will be relatively small compared to the grasslands that would have been needed for grazing.

Supply chain waste and losses are currently estimated at roughly one third of global production, which is about 1.3 billion tonnes a year (Gustavsson et al., 2011). The highest waste per capita occurs at the end of the food chain (at the retail and consumption stage) in North America (estimated at 115 kg/year/capita). In developing regions, most losses occur at the production to retailing stage, mostly related to inadequate storage systems. In the Trend scenario, these losses are projected to continue at current rates. Middle income countries with a burgeoning middle class take an intermediate position.

The growth in paper use and, to a lesser extent, the increasing demand for round wood for construction purposes results in increased global wood production. Globally the demand for traditional wood fuel is expected to decrease by 20% between 2010 and 2050 due to the shift towards modern (fossil) energy forms such as gas, oil products and electricity, made possible by higher incomes and enhanced access. The harvesting of wood products from natural and semi-natural forests and woodlands and the establishment of wood plantations will increase and results in a growing area of forest that is actively managed for production purposes (+3 mil. km^2). The area of forest plantations shows an increase of 30% between 2010 and 2050. Large unmanaged forest areas are used for some form of informal and lower intensity wood harvesting and collecting fuel wood.

2.3. Three pathways

Three pathways are designed to reduce the projected terrestrial biodiversity loss, according to the Biodiversity vision for 2050, while also achieving other environment related sustainable development objectives. The three pathways share the same assumptions for human population increase and economic development with the Trend scenario, which allows for better comparison.

A number of measures are implemented in all three pathways: the protected area network will expand to reach the Aichi biodiversity target of protecting at least 17% of the major ecosystems (but differs in the way this is implemented); biofuels production and wood plantations are only allowed on land currently not used for food production and not assigned as protected areas. Climate change is mitigated to levels not exceeding 2° increase by 2100, with relatively low use of bioenergy, to limit trade-offs between biodiversity and climate policies (see Table 2 for scenario assumptions).

In the *Global Technology pathway*, we assume that sustainability objectives are pursued mainly by large scale application of technological solutions. A high level of international coordination through, for example, trade liberalization, and the expansion of global markets drive the implementation of these responses in all world regions. In land use terms sustainable intensification in agriculture may lead to a “land sparing” effect, i.e. the most technological efficient use of one piece of land for production would allow sparing other land from conversion to agriculture and/or dedicate them to conservation (Balmford et al., 2005). Wood production will be concentrated in plantations to allow for efficient production of wood for paper, fuelwood and timber. The consumption of wood is assumed to be lower than in the Trend as new technologies replace considerable amounts of wood products, especially paper and traditional wood-fuel. Damage reducing techniques such as reduced Impact Logging (Putz et al., 2012) is only applied limitedly. To achieve the target for protected areas, 17% of the 8 different realms, according to the ecoregion system (Olson et al., 2001), is assumed to be fully protected, i.e. excluded from land use change and other activities, such as harvesting and hunting. The protected area system focusses on continuous natural areas away from existing agricultural land to minimise conflict with agricultural expansion. The large natural areas are not necessarily connected.

The *Decentralized Solutions pathway* mostly consists of solutions and technologies that can be implemented on a smaller scale and results in multi-functional mosaic landscapes and regional diversity, in line with regional priorities. Local and regional markets drive demand. The

Table 2
Key assumptions for measures introduced in each pathway.
Adapted from van Vuuren et al. (2015).

	Trend	Global Technology	Decentralized Solutions	Consumption Change
Access to food	Trends driven by historically observed relationships with income	*Trend*	Inequality in the distribution of global per capita consumption rates reduced so that all people are above the minimum consumption level in 2050	Inequality in the distribution of global per capita consumption rates reduced so that all people are above the minimum consumption level in 2050
Trade	No further liberalization beyond current policies	Full liberalization of trade in agricultural products	*Trend*	*Trend*
Consumption	Income driven consumption trends	*Trend*	*Trend*	Meat consumption levels off at a twice the level suggested for a healthy diet (Stehfest et al., 2009)
Supply chain waste and losses	At historical values	*Trend*	*Trend*	Waste and losses are halved (to 15% of production) (IMECHE, 2013)
Agriculture productivity	Based on trends in FAO scenario (Bruinsma, 2011)	In all regions, yield improvement 30% higher for crops and 15% higher for livestock than Trend scenario	In all regions, yield improvement 20% higher for crops and 15% higher for livestock than Trend scenario, only in those areas that are least vulnerable for biodiversity loss	In all regions, 15% improvement in crop yields.
Land planning	Default rules in IMAGE model	Expansion of agricultural areas close to existing areas in order to retain highly distinct land functions	Production areas shared with nature elements to reinforce ecological network. Keep at least 30% of landscape as nature elements.	*Trend*
Protected areas	No change in protected areas	17% of each of the 8 biodiversity realms protected. Protected areas far from agriculture.	17 of each of the 779 ecoregions protected. Protected areas close to agriculture	17% of each of the 65 realm/biomes combinations protected. Protected areas far from agriculture.
Forestry	Wood demand increases driven by increase in income	Forest plantations supply 50% of timber demand. 50% of selective logging is RIL (Putz et al., 2012).	Forest plantations supply 50% of timber demand. Selective logging is RIL	Forest plantations supply 50% of timber demand. Selective logging is RIL
Infrastructure	Impact of infrastructure on biodiversity increases based on historic correlations	*Trend*	Slower expansion of infrastructure (2050 values equal to 2030 values of *Trend*)	Slower expansion of infrastructure (2050 values equal to 2030 values of *Trend*)
Bio-energy	Default bio-energy potential (around 100–200 EJ/yr in 2050)	Constrained by sustainability criteria restricting potential for purposely grown bio-energy crops to less than 100 EJ/yr in 2050		

potential for ecological innovation in mixed land use systems where natural elements and production landscapes are interwoven may result in a "land sharing" effect (Balmford et al., 2005). Agricultural intensification is achieved by using ecological techniques, such as intercropping, agroforestry, and natural pest control, in combination with natural corridors interwoven with agriculture to enable the extensive use of ecosystem services (Pretty, 2008; Tittonell, 2014). We assume that agricultural landscapes comprise at least 30% of natural elements acting as corridors between natural areas and hence reducing fragmentation as well as contributing to the provision of ecosystem services. Wood demand is partly provided by plantations, that are established on abandoned, degraded lands. In semi-natural forests, wood is produced in a sustainable way by applying reduced impact logging (Putz et al., 2012). A large proportion of wood products is derived from local sources. The target for protected areas is implemented by protecting 17% of each of the 779 different eco-regions distinguished (Olson et al., 2001). The protected areas are allocated close to agricultural fields.

The *Consumption Change* pathway starts from implementing a set of behavioural changes in favour of less resource intensive consumption to reduce demand. This includes ambitious efforts to reduce waste, increase recycling in the production chain, reduced energy- and material-intensive lifestyle and a shift towards moderate consumption of meat and dairy, in line with health recommendations. While the narratives of the Global Technology and Decentralized Solutions pathways can be related to land "sparing" and "sharing", we label this the "caring" pathway, especially reflecting the importance of personal behavioural and consumption choices. This pathway assumes a reduction of 50% in food waste and losses, equalling 15% of the production (IMECHE, 2013). Productivity increase in agriculture in this pathway is only slightly higher than in the Trend scenario. Food consumption change is derived from the Willet diet, which main characteristic are a low meat and egg intake (Stehfest et al., 2009; Willett, 2001). A maximum consumption level for meat and eggs products is assumed to be twice the level recommended in the "Willett" diet (van Vuuren et al., 2012a). Wood consumption is influenced by substitution and recycling of products, especially paper, thus reducing wastes and lowering demand. Wood production will increasingly take place in plantations, preferably established on abandoned land. In semi-natural forest where selective logging takes place, there will be full adoption of reduced impact logging, similar to the Decentralized Solutions pathway. The protected area network is implemented by protecting 17% of each of the 65 realm-biomes combinations (Olson et al., 2001).

2.4. IMAGE/GLOBIO integrated assessment model framework

The Trend scenario and the three pathways were quantified and evaluated using the IMAGE integrated assessment model for the global environment (MNP, 2006; Stehfest et al., 2014) in combination with GLOBIO, a global model to assess biodiversity change (Alkemade et al., 2009; Schipper et al., 2016).

IMAGE assesses global environmental changes and impacts based on different assumptions with regard to socio-economic development and policy (MNP, 2006). The model framework consists of several coupled models that describe changes in land use and energy use, resulting from economic and demographic changes. These models are coupled with models representing the earth system, such as water flows, carbon cycling and natural vegetation to assess environmental impacts, including land use change climate change and water stress.

The model version 3.0 is extensively described in Stehfest et al. (2014). Here we highlight some relevant assumptions related to agriculture and forestry. The land use model is driven by the demand for food, feed, animal products, wood and bio-energy. The demand for agricultural products, except for bio-energy crops, is derived from the general equilibrium model MAGNET (Woltjer et al., 2014; Woltjer et al., 2011) that assigns agricultural production to 24 regions by using land supply curves based on relative production costs, derived from biophysical production determinants, such as local climate and soil conditions, from the IMAGE model. Demand for bio-energy crops (mostly second generation) is derived from the energy model TIMER integrated in IMAGE (Van Vuuren, 2007). Subsequently, the required land for agricultural use is translated into a $0.5 \times 0.5^{\circ}$ land use map by a set of allocation rules (Stehfest et al., 2014), including a preference for high yield grid cells and the proximity of other agricultural and urban areas. This iteration between the IMAGE and the MAGNET model is performed for the baseline and the pathways. The resulting total areas of cropland and grazing land for each region depend on the demand for agricultural products, environmental determinants and management factors.

Four wood production and forest management types are distinguished, including clear-cut and regrowth systems, selective logging, reduced impact logging and plantations, varying in productivity (Arets et al., 2011; Stehfest et al., 2014). Estimates and projections of wood demand and production are based on historical wood production data from FAO and the Global Trade Model for timber and pulp from the European Forest Institute (EFI) (Kallio et al., 2004). The EFI projections were slightly adjusted to fit the growth assumptions in baseline scenario (see also OECD, 2012). Timber production is modelled by using production estimates for forest types (FAO, 2012), and different rotation cycles for forest management types (Arets et al., 2011). The use of different forest management systems vary between world regions and this depends on the species composition of the forest, the market value of the wood species and other factors, such as accessibility and labour costs (Carle and Holmgren, 2008). Domestic demand for fuelwood is based on the TIMER model (Van Vuuren, 2007).

The impact of these changes on terrestrial biodiversity is assessed using GLOBIO, version 3.0 (Alkemade et al., 2009). The IMAGE output variables used include the global mean temperature increase, nitrogen deposition on land, land use changes, in terms of changes in areas dedicated to crops, to livestock grazing and to wood production. Areas of future agricultural intensity (km^2 per categories per region) are derived in two steps. First, we correlated regional estimates per intensity category from Dixon et al. (2001) with regional management factor estimates for the year 2000 from IMAGE. Secondly, we apply the resulting regression equation to the forecasted management factors from IMAGE. The different land use intensity categories are allocated to a 0.5 to 0.5 grid map, using both IMAGE input and the GLC2000 land cover map resulting in fractional land use categories for each grid cell (Visconti et al., 2011). An area of informal or "light" use of natural areas, including hunting and gathering of fuelwood and recreation, is called "encroachment" and simulated as a buffer zone around human settlements, indicated by the presence of cropland. Management of protected areas is assumed to achieve optimal conservation, implying no further land use change and no impact of other uses, including the encroachment effect, however some selective logging may be present in protected forests. The infrastructure map from the Global Roads Inventory Project (GRIP; Meijer et al., in prep.) is used to estimate changes in disturbance by infrastructure. Habitat fragmentation is assessed using changes of the size of patches of natural area. Patches were derived from the overlay of the GLC2000 land cover map with the GRIP roads map.

2.5. Indicator of biodiversity

The main indicator for biodiversity used in this study is the Mean Species Abundance of original species relative to undisturbed situations (MSA) (Alkemade et al., 2009). GLOBIO calculates impacts on biodiversity expressed as the relative change in Mean Species Abundance (MSA) in disturbed ecosystems compared to their mean abundance in original, undisturbed ecosystems. The index measures the level of "intactness" or "naturalness" of ecosystems. MSA is expressed in percentage changes, where 1% difference reflects the difference between an intact undisturbed ecosystem and a completely destroyed system of the size of 1.2 million km^2. Resulting changes in MSA were also attributed to different economic sectors, including the agricultural and forestry sector (see Supporting material Table 1 for attribution rules applied).

GLOBIO uses statistical relationships between the MSA and the level of change caused by single pressure factors. The model combines impacts of various drivers and allows to estimate the relative contributions of these different environmental drivers to changes in MSA (Alkemade et al., 2009). Interactions between the single factors are not considered in the model. These relationships are derived from a large number of published datasets, combined by meta-analyses. The impacts of land-use change are assessed by comparing the species abundance in the different land use categories with their abundance in original, neighbouring ecosystems or from the situation before disturbance. For cropland- and forestry categories the MSA estimates are based on Alkemade et al. (2009) and De Baan et al. (2013). MSA related to ecologically oriented production methods is assumed to be 40% higher than corresponding cropland intensity classes (Bengtsson et al., 2005; Reidsma et al., 2006). The effect of implementing Reduced Impact Logging (RIL) is assumed to be 15% higher than for selective logging (Putz et al., 2012). MSA values for grazing and grazing intensity are derived from Alkemade et al. (2013). The MSA value for encroachment, i.e. light use of ecosystems is derived from Alkemade et al. (2009). MSA values related to the impact of disturbance by roads and traffic are derived from Benitez-Lopez et al. (2010). GLOBIO applies a 1 km buffer along roads where disturbance affects the abundance of species. MSA estimates for fragmentation are derived from estimates for minimum area requirements for a large set of species (Verboom et al., 2014). MSA value changes related to climate change are based on published climate envelope models (Alkemade et al., 2011; Arets et al., 2014). Time lags of decades or centuries are likely to occur between the impact of climate change and actual extirpation or extinction (Fordham et al., 2016; Jackson and Sax, 2010; Menéndez et al., 2006). An average estimate of the lag time has not been established, therefore we assume a minimal lag time of 2 decades by dividing MSA losses from climate change by 2. MSA values related to Nitrogen deposition are published in Bobbink et al. (2010). MSA estimates and the publications behind them are available on www.globio.info.

3. Results

3.1. Land use change projection

Land use change is the main factor explaining biodiversity loss and is mainly driven by the dynamics within the agricultural and forestry sectors, which also includes bioenergy production. Fig. 1 shows the main changes in land use area for crop production, grazing and forestry between 2010 and 2050, in the Trend scenario and the three pathways.

In all scenarios areas for crop production and forestry are expected to increase between 2010 and 2050, whereas the area used for grazing will increase only in the Trend scenario. By 2050 areas used for crop production and grazing are expected to be considerably less in the pathways compared to the Trend scenario, with the exception of cropland areas in the Decentralized Solutions pathway, that shows a larger increase than in the Trend scenario. In the pathways intensified crop production reduces the area for crops compared to the Trend scenario, a small shift in the area of extensive cropland also reflect the tendency of intensification. The largest changes are expected in the Global Technology pathway, where cropland area decreases by 250 million ha especially in industrialised countries and in China and, to a lesser extent, in Sub-Saharan Africa. Intensification is much less in the Decentralized Solutions pathway, resulting in similar amounts of cropland areas as in the Trend scenario. The Consumption Change pathway takes an intermediate position.

The areas required for extensive grazing will in all pathways be lower than in the Trend scenario; and lower than in 2010. A substantial reduction of 405 million ha is, for example, expected in the Global Technology pathway. Livestock production is expected to be more dependent on feed from crop production systems.

All pathways show an increase in woody biofuels as a contribution to meet the 2° climate objective. The largest areas of woody biofuels are expected in the Decentralized Solutions pathway, necessary to compensate for the lesser focus on technological advanced energy systems.

In the Global Technology pathway, the total area of forest managed for wood production by 2050 will be 30% higher than in the Trend. The additional area is needed to compensate for the amount of wood that is no longer obtained from deforestation, which is reduced thanks to intensification in the agricultural sector. This demand cannot be covered by plantations, as newly-established plantations still need maturing to become productive (which takes 30 to 40 years) (Carle and Holmgren, 2008). In the Consumption Change pathway, reduced consumer demand for paper and timber leads to slightly lower forestry areas, about 25% increase compared to the Trend. In the Decentralized Solutions pathway, deforestation still occurs as increases in agricultural productivity are assumed to be lower than in the Global Technology pathway, resulting in a continuing supply of wood from deforestation. An increase in wood production from plantations is assumed in all pathways. Up to 50% of the total wood demand will be supplied by these highly productive systems by 2050. The area dedicated to plantation forestry will increase by 80% in the Global Technology Pathway, compared with 25% under the Trend. In the other pathways, the plantation area will increase by 65%.

The different allocation rules for protected areas at different levels of ecosystem aggregations in the pathways leads to differences in patterns and total areas of protection to achieve the Aichi Target on the expansion of protected areas to 17% (see Fig. 2). A focus on protecting smaller ecosystems as performed in Decentralized Solutions results in larger total protected areas, exceeding 17% of the terrestrial area globally.

3.2. Biodiversity projections and attribution to sectors

The Trend scenario projects a global terrestrial MSA loss of 9.5% on land from 2010 to 2050 representing a continuation of the historic trend since the 1970s (Fig. 3, for regional details see Table 2 in Supporting material). The largest losses are expected to occur in Sub-Saharan Africa and lowest losses in Russia and Central Asia (15% and 4% respectively). Land-use impacts from crop production, grazing and forestry together amount to almost 60% of the total worldwide loss of terrestrial MSA up to 2010 and 54% of the expected loss by 2050. Climate change impacts are expected to become increasingly important in this period (up to 20% by 2050), while factors related to infrastructure, and urban development increase steadily (up to 10%). Impacts of fragmentation and the direct use of ecosystems (encroachment) remain constant (at about 15%).

Fig. 4 shows the attribution of MSA loss to the various production sectors. Agriculture, including its role in deforestation, is the largest contributor to terrestrial biodiversity loss, but the relative contribution to MSA loss from the agricultural sector is decreasing compared to contributions from other sectors between 2010 and 2050. Energy and transport increasingly contribute to MSA loss through its climate change impacts and the impacts related to infrastructure expansion. The contribution of the forestry sector is relatively small, but increasing rapidly, in comparison to other sectors. Only a small proportion of MSA loss is attributed to industry, as the impacts of chemical pollutants and mining are virtually absent in the models, and energy use by the industrial sector is attributed to the energy sector. The impacts attributed to direct use of natural systems, including hunting, gathering, recreation and tourism show a considerable, but slightly decreasing proportion.

From the MSA loss of 9.5% by 2050 observed in the trend scenario and the assumed reductions of loss rates in developed and developing

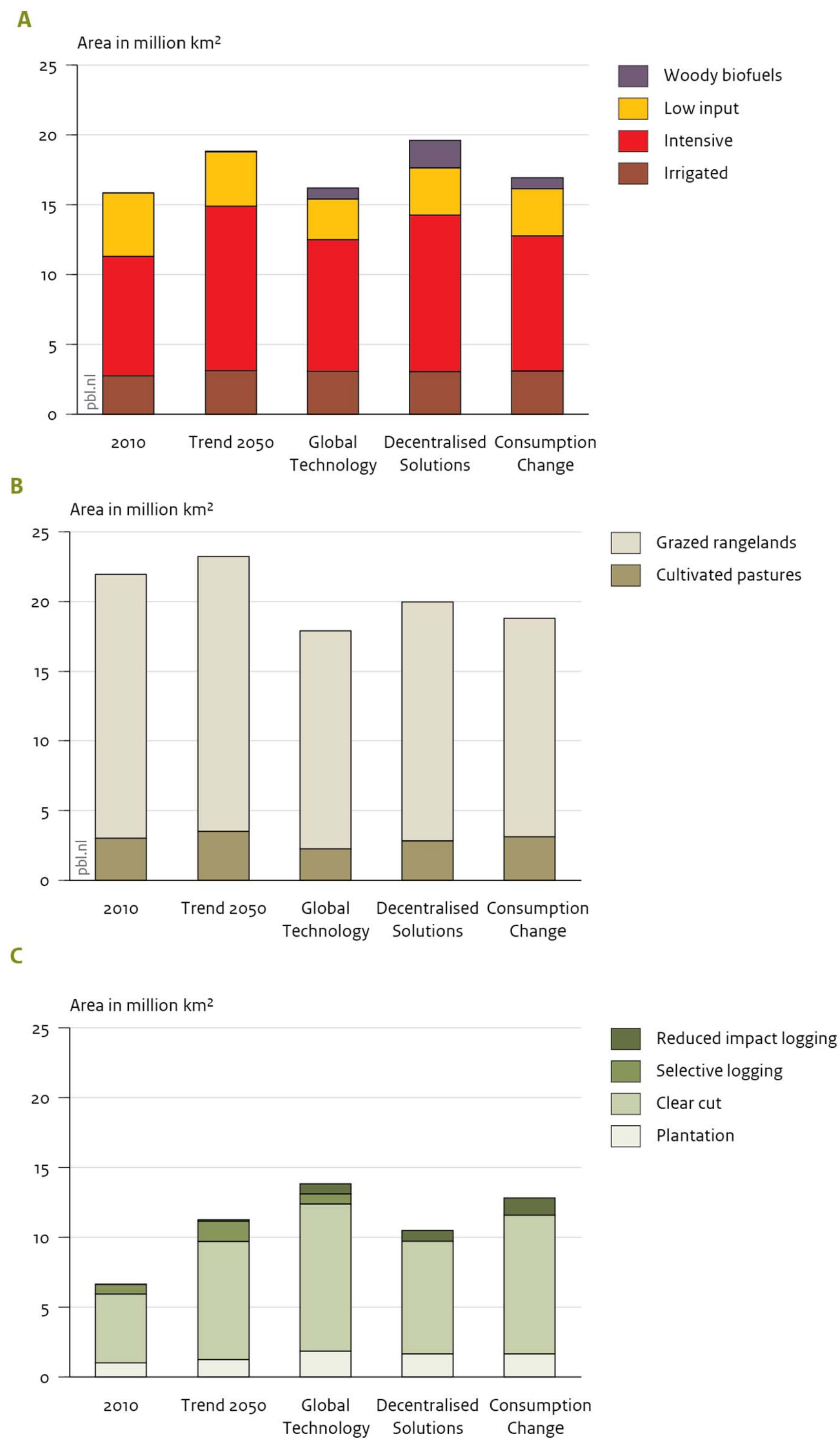

Fig. 1. Areas used for (1a) crop production, (1b) grazing and (1c) forestry (Trend and pathways). Total land area is about 130 million km^2.

countries, the target is 5.7% avoided loss globally. The pathway analysis resulted in avoided MSA losses for the Global Technology Pathway of 4.4%, Decentralized Solution of 4.8% and Consumption Change 4.5%., which is 10–15% below the target.

Fig. 5 shows where either the Decentralized Solutions pathway (land sharing) or the Global Technology pathway (land sparing) or both result in 5% higher MSA values than in the Trend scenario. Regions where the Global Technology pathway offer potential include the Congo basin, the western part of US and Mid China, areas currently having large natural areas, but expected to affected in the Trend scenario. Regions, such as South Asia, Eastern Europe and Eastern US, where the Decentralized Solutions pathway results in higher MSA values are currently extensively used for agriculture, and are continued to be used in the Trend scenario. The regions where both pathways result in a 5% higher MSA include Southern part of South America, Turkey and Northern Africa are currently a mixture of intensive agriculture and substantial natural areas. Due to different designs of the pathways the type of biodiversity preserved will differ. The Global Technology pathway shows more natural biodiversity in large and remote areas whereas in the Decentralized Solutions pathway biodiversity is

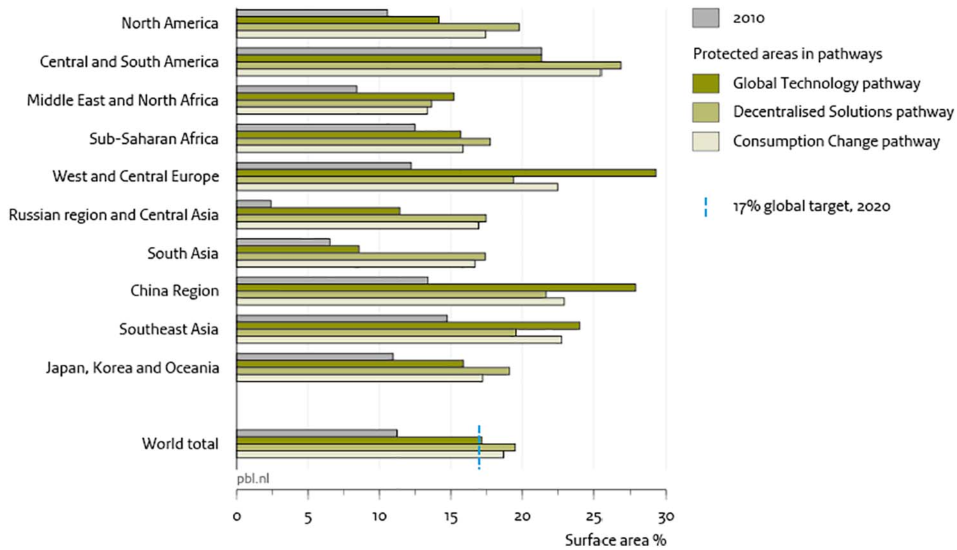

Fig. 2. Protected areas under Trend scenario and pathways.

preserved in mixed and mosaic landscapes, increases in agricultural areas and tends to be maintained or may even decrease in the remaining natural areas. The Consumption Change pathway shows least pronounced change as the focus of this pathway is on reducing demands rather than changing land-use patterns.

3.3. Contributions of the agricultural sector to reduce biodiversity loss

About 60–72% of the avoided loss in the three pathways can be attributed to options within the agricultural sector (Fig. 6). In the Global Technology pathway increased productivity of both crop and livestock systems is the major factor to reduce MSA loss, accounting for 64% of the avoided loss. Climate impacts from land use as well as Nitrogen deposition are reduced in all three pathways compared to the trend. In the Decentralized Solutions pathway, increased productivity is still a major factor contributing about 40% of the avoided loss moreover the reduced fragmentation resulting from the increase of mosaic landscapes and the increased MSA on agricultural land resulting from changing production methods contribute for about 10% to the avoided MSA loss. In the Consumption Change pathway, the reduced demand for agricultural products, resulting from changing consumption patterns and reducing wastes contribute to avoided MSA loss by about 25%.

Avoided losses differ between regions (Fig. 7), ranging from over 5% in Europe and the China region and less than 2% in Central Asia. In Europe, the China Region, Sub-Saharan Africa and in Japan, Korea and Oceania the largest avoided losses are within the Global Technology pathway. In the Americas and South-East Asia largest avoided losses are within the Consumption Change scenarios; whereas in Middle East and North Africa, the Russian region and Central Asia and in South Asia avoided losses are highest in the Decentralized Solutions pathways.

3.4. Contributions of the forestry sector to reduce biodiversity loss

By 2050 the avoided MSA loss attributed to the forestry sector is very limited or still absent. The pathways for the forestry sector have both positive and negative effects on MSA loss, as compared to the Trend scenario (see Fig. 8). A net biodiversity loss is projected for 2050 in two out of three pathways. Only in the Decentralized Solutions pathway 0.4% MSA loss, is avoided compared to the Trend. The limited contribution of the forestry sector to reduce MSA loss in the Global Technology and Consumption Change pathways is a consequence of measures that aim at replacing the timber harvesting from natural forest with harvesting from plantations. However by 2050 newly established plantations after 2010 will not yet be productive. The avoided deforestation by the agricultural sector leads to the necessity of increased harvesting from natural forest by clear cut harvesting or selective logging. In the Decentralized Solution pathway a proportion of the wood from deforestation will still be available on the global market. In the analysis deforestation is attributed to the agricultural sector. Establishing high-productive plantations reduces the areas needed for

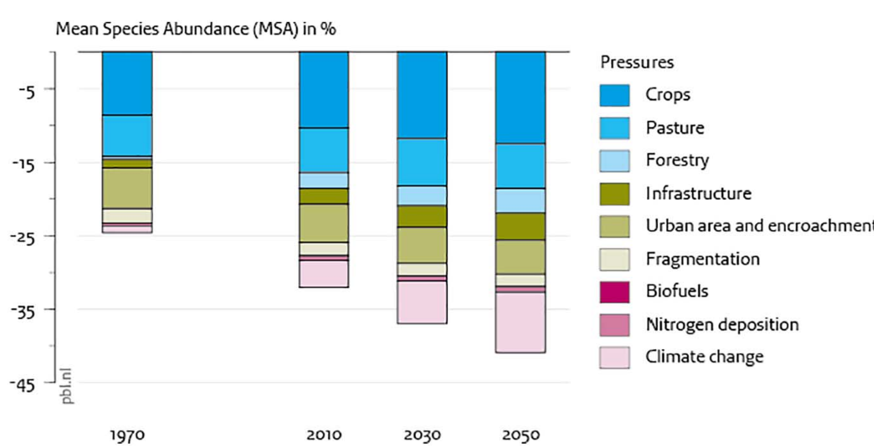

Fig. 3. Global terrestrial MSA loss by pressure factor under the Trend scenario.

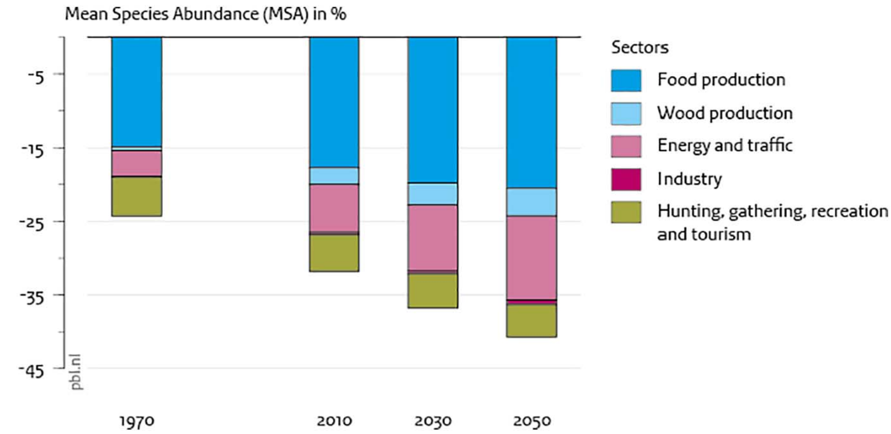

Fig. 4. Attribution of terrestrial MSA losses to different production sectors under the Trend scenario.

wood production, but will only be productive after more than 30 years. A positive effect for biodiversity can therefore only be expected after 2050.

Regional details are provided in Fig. 9. Avoided MSA loss is highest in the China region, West and Central Europe, and the Americas, while Sub Saharan Africa and South Asia and Southeast Asia show net increases of MSA loss. Options for establishing additional plantations are mostly found in regions with widespread recent deforestation where the land is abandoned or used for extensive cattle ranching (Southeast Asia, Central and South America).

4. Discussion

This paper shows possible contributions of changes in the agriculture and forestry sectors to reduce their impact on biodiversity and emphasizes the potential of transformative changes for biodiversity in the agricultural and forestry sectors. The three pathways that we analysed indicate an “option space” with different combinations of technological and behavioural options. These pathways are not the only possible pathways, nor are they preferred development trajectories. The pathways do not entirely meet the targets set in the back-casting analysis. This would either require increasing the efforts in the pathways as discussed below or looking for different combinations of pathways, also taking into account specific regional contexts. Especially a combination of the Consumption Change pathway with either the Global Technology or Decentralized Solutions pathway will result in better results for biodiversity. Also note that not all possible measures are considered in this study, such as the restoration of degraded lands, the recovery of abandoned lands and mitigating impacts related to infrastructure development and urbanization.

The current analysis does however show options for agriculture and forestry to substantially contribute to achieving biodiversity goals in the coming decades. Given expected increasing demands for natural resources as well as limited progress in the sectors to produce more biodiversity friendly outcomes, this requires transformative changes in for example technological advancements and consumption preferences. Below we discuss the most important options we have analysed, for a further discussion of policy implications see Kok et al. (2014).

4.1. Agricultural productivity increase

Increasing agricultural productivity is a corner stone for all three pathways; the productivity increase required to achieve long-term sustainability goals range from 0.8–1.2% per year. This requires bending the current diminishing trend in the rate of productivity increase (Bruinsma, 2011; Grassini et al., 2013). Approaches to achieve a higher productivity differ largely between the Global Technology and Decentralized Solutions pathway.

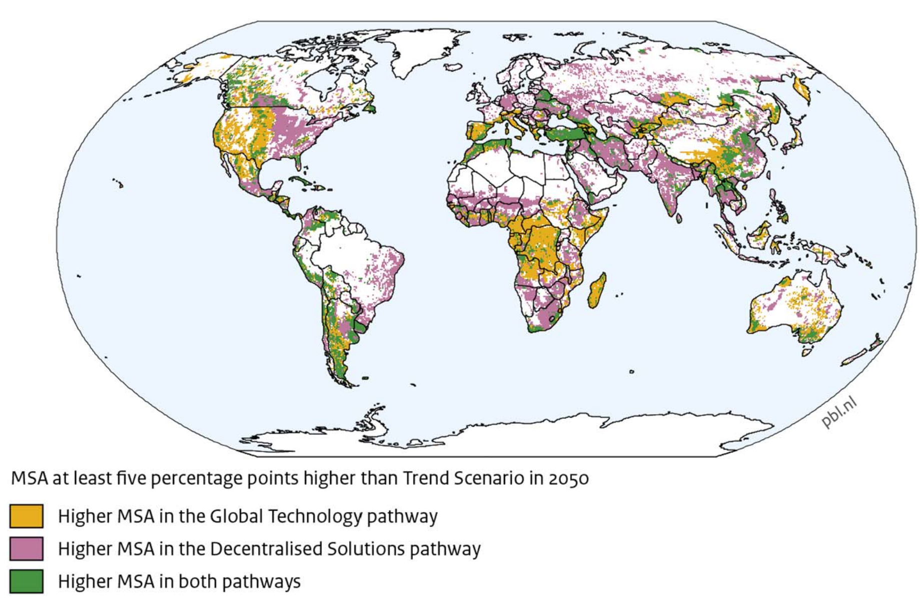

Fig. 5. Areas with at least 5% avoided loss in pathways, compared to the Trend scenario.

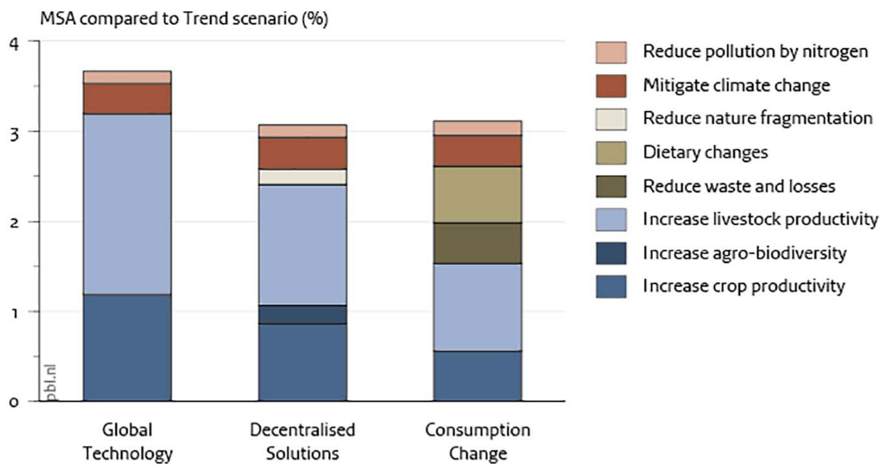

Fig. 6. Contributions of various options within the pathways to reduce global biodiversity loss in the agricultural sector.

Many authors emphasize the potential of technological improvements, as was assumed in the Global Technology pathway, especially in regions where potentials are not being used completely (closing yield gaps) by applying existing technologies and improved practices (Foley et al., 2011; Neumann et al., 2010; Tilman et al., 2011). In some regions only minor yield increases have been achieved in the past 20 years, whereas in others the yield increase was fading out in the same period (Bruinsma, 2011; Grassini et al., 2013; Ray et al., 2013). New technologies for yield improvement are required in these areas where productivity is already high, especially if the pathway suggested in Global Technology is to be followed. Advanced technologies can be developed and applied in regions with already high productivity (Peltonen-Sainio et al., 2009; Ray et al., 2013). We assumed yearly yield increases twice the projected yield increase for the period 2006–2050 by FAO (Bruinsma, 2011) and at the high end of a range of other projections (McIntyre et al., 2009; van Dijk and Meijerink, 2014). Challenges remain to avoid the negative side impacts on biodiversity (including in soils) of intensive agriculture by for example excessive pesticide use, non-sustainable water use, high energy input, erosion or over-fertilization (van Noordwijk and Brussaard, 2014). However, some current trends suggest that, on average, environmental impacts of agriculture are decreasing. For example the decrease in global average nutrient use efficiency has been stabilized and is slightly increasing in recent years in some regions (Lassaletta et al., 2014). Strong emphasis on resource efficiency through technological improvements, agronomic optimisation of the farm environment, animal breeds and crop varieties that perform best under these optimised conditions, may mitigate environmental impacts further. We therefore conclude that technically increasing productivity of agricultural production, while avoiding environmental impacts, referred to as sustainable intensification e.g. (Garnett et al., 2013), may be feasible, but require investments to close the yield gap and research to develop novel technologies, as the challenge remains to reduce environmental impacts.

The potential of the optimal use of ecosystem services, or ecological intensification is hardly explored, but may potentially reduce or avoid environmental impacts, while increasing productivity (Bianchi et al., 2013; Bommarco et al., 2013; Tittonell, 2014). A large variation of approaches exists to achieve increased production while retaining or using ecological processes and biodiversity. Examples are agroforestry, organic farming, and the ecosystem services approach (De Groot et al., 2010; Pretty, 2008; Tittonell, 2014; van Noordwijk and Brussaard, 2014). The productivity of these systems is still lagging behind in comparison with more conventional systems (de Ponti et al., 2012; Ponisio et al., 2015). A main reason is suggested to be the lack of research to improve productivity in, for example, organic farming (Tittonell, 2014). Other authors point to the seemingly inherent limitations of organic farming (de Ponti et al., 2012). In areas currently facing considerable yield gaps ecologically oriented techniques may increase productivity considerably (Tittonell, 2014; van Noordwijk and Brussaard, 2014). Research is needed to design of new agricultural systems that combine ecological resilience with efficient technologies to avoid labour-intensive agricultural practices. Precision techniques may offer a range of new opportunities (e.g. Bianchi et al., 2013; Bommarco et al., 2013; Boyer et al., 2011; Tscharntke et al., 2012). Besides many advantages of ecologically oriented production methods such as reducing environmental pollution of nutrients and pesticides reducing the

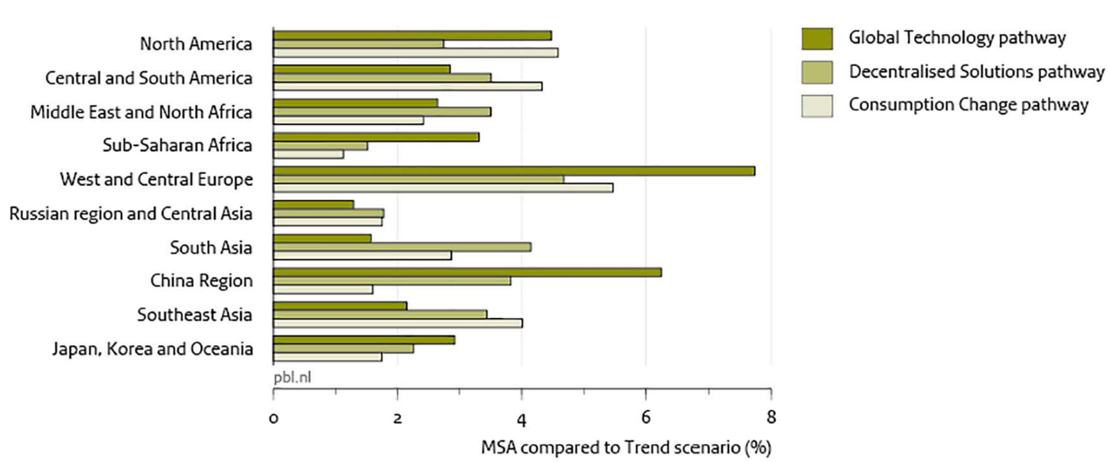

Fig. 7. Regional differences in pathways for preventing biodiversity loss in the agricultural sector.

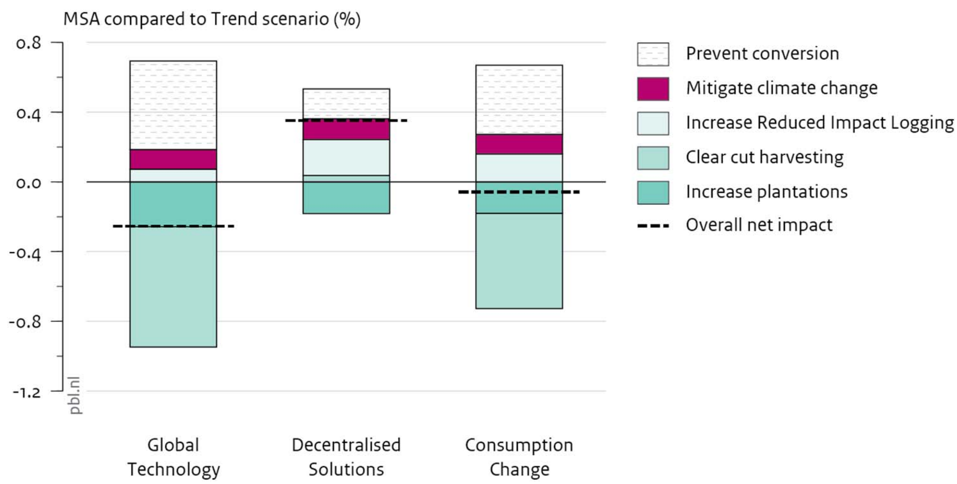

Fig. 8. Biodiversity changes in the different pathways as a consequence of changes in the wood production, forestry and changes in deforestation driven by changes in agricultural yields.

contribution of climate change by reduced CO_2 emissions and increased carbon sequestration, and improving soil quality and water retention, the potential for productivity increase is currently still limited and more land is needed to produce similar amounts of food as compared to technological improvements (Erb et al., 2016).

4.2. Spatial arrangements

Increasing productivity is an important condition for reducing the land area needed for agricultural production and consequently reducing biodiversity loss. However many authors argue that land area actually used only reduces if simultaneous measures to protect natural areas are taken (Ewers et al., 2009; Phalan et al., 2016; Rudel et al., 2009). At the same time ecological intensification will only be successful if large areas within the agro-ecological matrix are reserved for natural elements (Perfecto and Vandermeer, 2010). Thus, the spatial arrangement of protected areas and natural elements matter as part of a larger spatial planning effort. Our analyses show that both the land sparing and the land sharing strategies may lead to reducing biodiversity loss, but the type of biodiversity preserved and the spatial distribution of the reduced losses differ largely (see Fig. 5). The "land sparing" strategy, as implemented in the Global Technology pathway, implies the protection of vast natural, pristine, areas, with high biodiversity levels. However, this strategy may not always work because of rebound-effects in which increased yield may lead to increased conversion of natural lands, also referred to as the "Jevon's paradox" (Ceddia et al., 2014; Hill et al., 2015). The "land sharing" strategy, as implemented in the Decentralized Solutions pathway, may avoid these effects, and improves the connectivity between natural areas by the abundance of natural elements within the "agro-ecological" matrix.

4.3. Consumption change and demand for agricultural products

A major contribution to achieving biodiversity goals is to decrease the demand for agricultural products by consumption change and reducing food wastes. Especially by reducing consumption of meat and dairy products the areas required for agriculture and the emissions of greenhouse gases and nutrients may be reduced substantially (Machovina et al., 2015; Stehfest et al., 2009). A diet change towards less meat consumption will also improve human health (Machovina et al., 2015). However per capita meat consumptions is increasing globally and is expected to increase in the coming decades with rising population and incomes in most world regions, making dietary changes towards less meat consumption more difficult to achieve (Henchion et al., 2014). Reducing wastes throughout the entire production consumption chain has high potential for reducing the demand for agricultural products (Erb et al., 2016; Parfitt et al., 2010). The main food wastes in Sub-Saharan Africa and South and Southeast Asia are related to post harvest losses at field level or are due to limited storage capacities, which can be largely improved by existing technics for food storage and transportation (Lipinski et al., 2013; Parfitt et al., 2010). In Europe and North America the main losses are related to consumption and retail (Gustavsson et al., 2011; Lipinski et al., 2013). Many options exist to reduce wastes by retail and consumption including for example public campaigns or portion size reduction in restaurants (Lipinski et al., 2013).

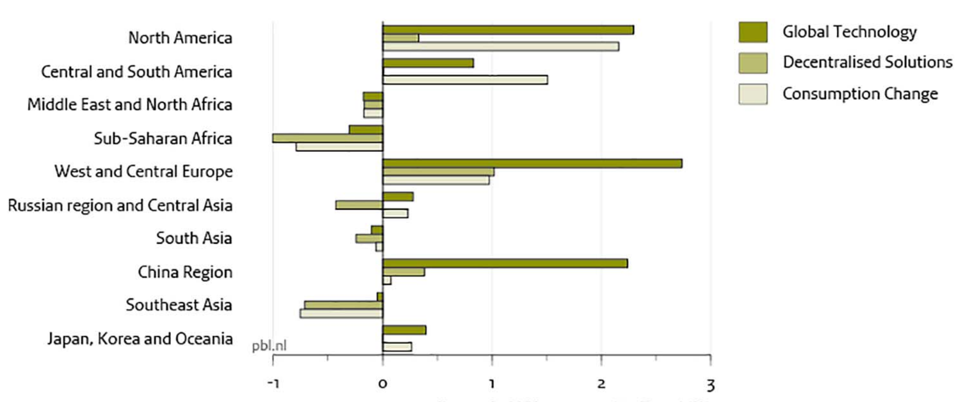

Fig. 9. Regional differences in pathways for preventing biodiversity loss as a consequence of changes in the wood production, forestry and changes in deforestation driven by changes in agricultural yields.

4.4. Forestry challenges and options

Successful efforts to reduce deforestation by for example increasing agricultural productivity, or reducing demands for agricultural products will result in decreased availability of wood from conversion. As shown in the Global Technology and Consumption Change pathways, the forestry sector, to fulfil the demands, will need to increase the areas for plantations and other forms of permanent forestry. Currently the area of plantations is increasing (FAO, 2012), but the pathways assume a considerable acceleration of implementing plantations potentially preventing harvesting from natural forests and therefore reduced biodiversity losses from forestry. These effects are only expected after 2050 (Ten Brink et al., 2010). However, establishing plantations leads to additional loss in forest biodiversity as plantations contain less biodiversity then other wood production systems, such as selective logging (Alkemade et al., 2009; Gibson et al., 2011; Newbold et al., 2015). Harvesting from natural forests remains important and will increase as demands for wood are increasing. Better management will contribute to maintain biodiversity in these forests (Putz et al., 2001).

4.5. Limitations and strengths

Clearly, the IMAGE and GLOBIO model and the scenarios used here include a wide range of assumptions. This study did not explicitly quantify the uncertainty arising from these model and scenario assumptions although the differences across the various pathways obviously provide a key illustration of uncertainty. The baseline assumptions in the OECD scenario are somewhat in the middle of the current literature with respect to population and economic growth and trends in energy and land use. It is therefore indicative for a situation of medium challenges for biodiversity. Covering a wider baseline range (such as in the Shared Socio-economic Pathways, Riahi et al., 2017) would allow also exploring high and low challenges.

Uncertainty in land use projections in the integrated assessment models (Prestele et al., 2017) showed large differences between models, but evaluation of similar scenarios show similar results for different models. This makes the differences between the scenarios more robust than the exact outcomes of the scenarios. Still, the contribution of individual options within the pathways should be mostly seen as explorative. The outcomes are not only influenced by the elements in the models and how they were implemented, but also by the factors that were not included. In the GLOBIO model no impacts of mining, invasive species, pollutants other than Nitrogen are included, which may have resulted in overestimating the reduction of biodiversity loss. Furthermore the goals analysed are not static. For example the 2015 Paris Agreements introduced the objective of going towards 1.5 °C (well below the 2° target analysed in this study). This may create a higher demand for bioenergy as the coupling bioenergy (BE) and Carbon Capture and Storage (CCS) (BECCS) to create negative emissions is an important contribution to stay well below 2° (Smith et al., 2013b).

Furthermore, the model-approach applied here does not allow to analyse the economic costs and benefits of these pathways and “feed” that back into the economic growth path. Hence the analysis here should be considered as focussing on their bio-physical potential and impacts on biodiversity. It indicates potential of options and efforts required to meet them, without specifying economic costs and benefits. This is important, but requires further analysis with suitable economic tools. A stronger focus on costs could provide additional insights on the required investments and economic feasibility of the scenarios. Note however, that currently these feedbacks from socio-ecological systems to the economy are still missing in most integrated assessment models (Rosa et al., 2017).

Some of the pathways and the Trend scenario were evaluated using different methods (Leadley et al., 2014; Visconti et al., 2016). Their results consistently show improvements of both the Red List Index and the geometric mean abundance metrics for the pathways compared to the Trend scenario. GLOBIO uses the MSA to describe biodiversity and provides a measure for achieving the 2050 vision for biodiversity. We are aware that MSA has only a limited focus on the broad concept of biodiversity, as it mainly describe the difference between humanly disturbed ecosystems and natural systems. A wider range of biodiversity indicators is needed to improve robustness of scenario analysis for biodiversity.

The analysis in this paper goes beyond earlier model-based scenario assessments on the future of biodiversity (Pereira et al., 2010). The model-based scenario assessments have been based on socio-economic storyline approaches (see also (IPBES, 2016)) that explore biodiversity implications of alternative possible futures. These explorative scenario studies do not explore the effects on biodiversity of specific options as is, for example, done in McIntyre et al. (2009), Ten Brink et al. (2010), and OECD (2012). These policy screening scenarios revealed that no single option is sufficient to reduce biodiversity loss sufficiently to reach any biodiversity target. Implementing combinations of options as were analysed in this paper was therefore recommended.

This paper shows that combining options into target-seeking pathways provides new insights in how to achieve biodiversity objectives within a broad set of environment related sustainability objectives. We suggest that the pathways presented in this paper can challenge policy and decision-makers at different levels to consider how their decisions might move them towards one pathway or another and how that could help or complicate achieving biodiversity targets. The analysis could for example inform preparations for the new CBD Strategic Plan on Biodiversity (2020 – 2030).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.03.003.

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