PBL Netherlands Environmental Assessment Agency

THE GLOBIO MODEL

A technical description of version 3.5

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PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the field of environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

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PREFACE

The ongoing worldwide decline of biodiversity brings about a clear demand for quantitative models able to project future biodiversity in response to anthropogenic pressures. The GLOBIO model is designed to assess past, present and future human-induced changes in terrestrial biodiversity at regional to global scales. The model is built on a set of quantitative relationships that describe six anthropogenic impacts on biodiversity: impacts of land use, climate change, atmospheric nitrogen deposition, disturbance by infrastructure, habitat fragmentation due to land use and infrastructure, and human encroachment. Biodiversity responses are quantified as the mean species abundance (MSA), which expresses the mean abundance of original species in disturbed conditions relative to their abundance in undisturbed habitat, as an indicator of the degree to which an ecosystem is intact.

Several publications describe (parts of) the GLOBIO model. General descriptions of the model are provided by Alkemade *et al.* (2009) and Stehfest *et al.* (2014). In addition, there are various papers available providing a more detailed description of the cause-effect relationships applied and the empirical underpinning thereof (Alkemade *et al.*, 2011, Alkemade *et al.*, 2013, Arets *et al.*, 2014, Benítez-López *et al.*, 2010, Bobbink *et al.*, 2010, Verboom *et al.*, 2014). The present document contains a technical description of the GLOBIO model, i.e., a coherent overview of the input data, modelling steps and parameter values used to calculate MSA. The report first describes the general modelling approach that is followed in GLOBIO. Thereafter, it explains the model parameterization for the six anthropogenic impacts on biodiversity that are currently included. The final section of this report explains how the model results are combined across the six impacts in order to arrive at an overall MSA value. The description is based on version 3.5 of the model. Corrections and modifications that have been implemented since are documented in subsequent addenda at the end of the report.

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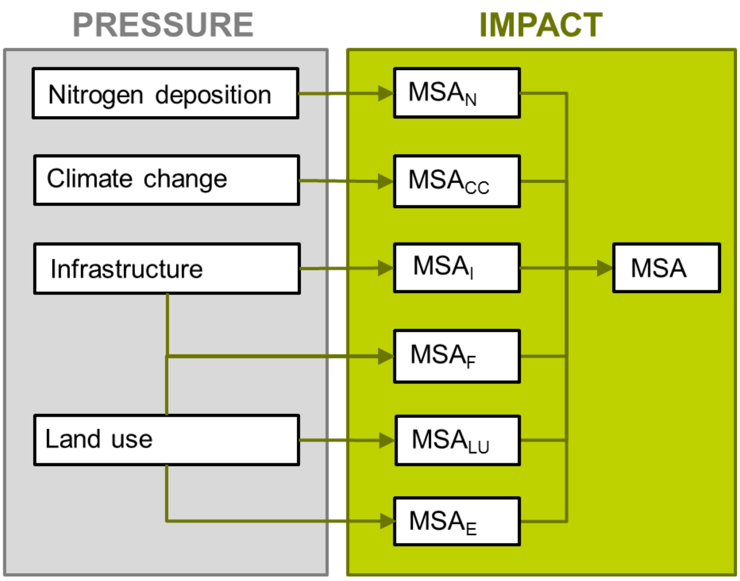
1. Modelling approach: overview

1.1 Cause-effect relationships

The core of the GLOBIO model consists of a set of quantitative relationships that describe how biodiversity, expressed as the mean species abundance (MSA), responds to anthropogenic environmental pressures. MSA represents the mean abundance of original species in relation to a particular pressure as compared to the mean abundance in an undisturbed reference situation. Pressures included in the GLOBIO model are climate change, atmospheric nitrogen deposition, land use, infrastructure and human encroachment. Per pressure, multiple cause-effect pathways are possible (Figure 1.1). For example, infrastructure may affect MSA via habitat fragmentation (barrier effect), but also because the proximity of infrastructure disturbs the remaining surrounding natural habitat (edge effect). In total six impacts are distinguished, each quantified in terms of MSA (Figure 1.1):

1. MSA due to the eradication or modification of natural habitat through land use (MSA_{LU}).
2. MSA due to an increase in global mean temperature induced by climate change (MSA_{CC}).
3. MSA due to eutrophication induced by atmospheric nitrogen deposition (MSA_{N}).
4. MSA due to the disturbance of natural habitat through the proximity of infrastructure (MSA_{I}).
5. MSA due to the fragmentation of natural habitat by both land use and infrastructure (MSA_{F}).
6. MSA due to human encroachment, i.e., activities like hunting and recreation in otherwise natural habitats, which are correlated to land use (MSA_{E}).

Figure 1.1 Schematic representation of the cause-effect relationships included in the GLOBIO model (version 3.5).



Per impact, the MSA values are quantified based on a synthesis (meta-analysis) of empirical species monitoring data in disturbed habitat compared to an undisturbed reference situation, reported in comparative studies derived from the literature. Per study, MSA values are calculated for different impact/effect levels, as follows (Alkemade *et al.*, 2009, Benítez-López *et al.*, 2010):

1. For each species present in the reference situation, a ratio is calculated between its abundance (number, density, cover percentage) observed at a certain impact/effect level and its abundance in the undisturbed reference situation.
2. These ratios are truncated at 1, i.e., increases in abundance in response to anthropogenic pressures are neglected.
3. Per impact/effect level, an arithmetic mean value is calculated of the truncated abundance ratios of all species considered in that study. This value represents the MSA for that impact/effect level.

Cause-effect relationships are then established either by regressing the MSA values obtained from the different studies to the pressure variable of concern (for continuous variables, like temperature change and nitrogen deposition) or by calculating a mean and standard error of the MSA values per impact/effect level or category (for categorical or ordinal variables, like land use) (Alkemade *et al.*, 2013, Alkemade *et al.*, 2009, Arets *et al.*, 2014, Benítez-López *et al.*, 2010, Verboom *et al.*, 2014).

In total, six major taxonomic groups are covered by GLOBIO, which is largely a reflection of the availability of literature data suitable to quantify MSA: mammals, birds, reptiles, amphibians, terrestrial invertebrates and vascular plants (Table 1.1). In principle, all MSA values obtained from the literature are combined in order to establish the cause-effect relationships, i.e., data of different taxonomic groups are combined. However, in some cases a particular taxonomic group is assumed not to be affected by a particular impact (e.g., plants are assumed to be not significantly affected by infrastructure disturbance; see Table 1.1). In that case, a correction is applied afterwards, whereby the MSA per taxonomic group accounts for one-sixth of the total MSA, as follows (Eq. 1.1):

$$MSA_X = \sum_{T=1}^{T=6} \frac{1}{6} \cdot MSA_{X,T} \qquad \text{(Eq. 1.1)}$$

where MSA_X represents the overall MSA in relation to impact *X* and $MSA_{X,T}$ represents the MSA of impact *X* for taxonomic group *T*. MSA_x is then calculated based on the generic overall MSA value for the groups that are affected, while setting the MSA value for the groups that are not affected to 1. For example, the MSA for infrastructure disturbance, which is assumed to affect vertebrate species only, is calculated as $MSA_I = 4/6 \cdot MSA_{I,\text{vertebrates}} + 2/6 \cdot 1$.

Table 1.1 Taxonomic groups covered for each of the six impacts.

	Taxonomic groups					
	Mammals	Birds	Amphibians	Reptiles	Invertebrates	Vascular plants
MSA_{LU}	yes[a]	yes[a]	yes[a]	yes[a]	yes[a]	yes[a]
MSA_{CC}	yes[b]	yes[b]	yes[b]	yes[b]	yes[b]	yes[b]
MSA_{N}	yes[c]	yes[c]	yes[c]	yes[c]	yes[c]	yes[c]
MSA_{I}	yes[d]	yes[d]	yes[d]	yes[d]	no	no
MSA_{F}	yes[d]	yes[d]	yes[d]	yes[d]	no	no
MSA_{E}	yes[d]	yes[d]	no	no	no	no

[a] based on MSA values aggregated over all six taxonomic groups, [b] based on a cause-effect relationship quantified for vascular plants and vertebrates; [c] based on a cause-effect relationship quantified for terrestrial plants; [d] based on MSA values for birds and mammals.

1.2 Application and integration

To quantify the individual and combined effects of the various anthropogenic pressures, GLOBIO applies the cause-effect relationships in a spatially explicit way. First, the cause-effect relationships per impact are used to translate raster maps of the underlying pressure variable into maps with impact-specific MSA values. Next, the maps with the MSA values per impact are combined to arrive at an overall MSA (Figure 1.1). Two options are available to integrate the different MSA values across the impacts, depending on the type of interaction assumed. If a particular pressure is assumed to take precedence over the others, the combined impact is assumed equal to the single worst or dominant impact (Folt *et al.*, 1999), i.e., the MSA value for this dominant impact is selected. Alternatively, it can be assumed that pressures act independently, i.e., that the sensitivity of species to different pressures is not correlated. In that case, the overall MSA value is calculated by multiplying the MSA values corresponding with the individual impacts (Eq. 1.2) (Traas *et al.*, 2002).

$$\mathrm{MSA}_i = \prod_{X=1}^{X=6} MSA_{X,i}$$

(Eq. 1.2)

where MSA_i is the overall MSA for map unit *i* and $MSA_{X,i}$ is the MSA related to impact *X* in map unit *i* (as calculated according to Eq. 1.1). It is also possible to combine the two approaches. In GLOBIO it is assumed that the direct land-use impacts of agriculture (cropland) and urban areas take precedence over all other impacts, i.e., that the loss in MSA due to direct land-use impacts is so severe in croplands and urban areas that there are no further losses of MSA due to other pressures. In areas other than cropland and urban areas, the MSA values are multiplied. This yields the following equation (Eq. 1.3):

if LU = cropland OR LU = urban, $\mathrm{MSA}_i = \mathrm{MSA}_{\mathrm{LU},i}$

else $\mathrm{MSA}_i = \mathrm{MSA}_{LU,i} \cdot \mathrm{MSA}_{CC,i} \cdot \mathrm{MSA}_{N,i} \cdot \mathrm{MSA}_{I,i} \cdot \mathrm{MSA}_{F,i} \cdot \mathrm{MSA}_{E,i}$ (Eq. 1.3)

where MSA_i is the overall MSA for map unit *i* and $MSA_{X,i}$ is the MSA corresponding with the impacts of land use (LU), climate change (CC), atmospheric nitrogen deposition (N), infrastructure (I), habitat fragmentation (F), and human encroachment (E).

2. Direct impacts of land use

2.1 Construction of the GLOBIO land-use map

2.1.1 Baseline situation (reference year 2000)

Land-use data in GLOBIO 3.5 is compiled from different sources. As a starting point, the GLC2000 map is used, which is a global land-cover map at a resolution of 30 by 30 arc seconds (~ 1 by 1 km at the equator) published by the Joint Research Centre (Joint Research Centre, 2003). Its legend includes 23 land-cover classes (Table 2.1). Because land-cover maps derived from remote sensing data do not provide adequate information on anthropogenic land use, the GLC2000 map is combined with various other data sources to arrive at a land-use map. This procedure includes four main steps:

1) The GLC2000 map is overlayed with a map of protected areas, derived from the world database on protected areas (WDPA) of UNEP-WCMC and IUCN (version 2011), in order to identify which of the GLC2000 grid cells belong to protected area. For compatibility with the other pressure data, the information on the GLC2000 map is then changed to a resolution of 0.5° by 0.5° (~ 50 by 50 km at the equator), whereby the proportion of each land-cover type per grid cell (both protected and non-protected) is stored as attribute of that grid cell.

2) Next, an estimate is made of the proportions of cropland and pasture per 0.5° by 0.5° grid cell, based on the proportions of grassland (GLC2000 classes 12-14; see Table 2.1, first column), cropland (cultivated and managed areas; class 16) and mixed/mosaic classes (classes 17 and 18) as well as the proportion of unknown landcover (class 23), according to a procedure developed by Klein Goldewijk *et al.* (2007). Per grid cell, the proportions of cropland and pasture are calculated with the following equations (Visconti *et al.*, 2011):

   $$P_{crop} = 0.9*P_{16} + 0.5*P_{17} + 0.3*P_{18} + 0.5*P_{23} \quad \text{(Eq. 2.1)}$$

   $$P_{pasture} = 0.5*P_{12} + 0.9*P_{13} + 0.9*P_{14} + 0.1*P_{16} + 0.3*P_{17} + 0.6*P_{18} + 0.5*P_{23} \quad \text{(Eq. 2.2)}$$

   where P_x represents the proportion of a given land-use or land-cover class. Here, pasture represents a new class not present in the original GLC2000 map (class 30; see Table 2.1, second column). After subtraction of the cropland and pasture, the remainder of the mixed class 17 is considered forest and the remainder of the classes 12, 13, 14 and 18 is considered natural grassland (see Table 2.1, second column).

3) Next, the proportions of cropland and pasture in the GLOBIO land-use map, as obtained through Eqs. 2.1 and 2.2, are adjusted in order to meet the regional totals of cropland and pasture as estimated by the IMAGE model (which in turn are calibrated on FAO data). This is done in order to make the baseline land-use map consistent with past and future land-use maps, which rely on IMAGE land-use projections (see further section 2.1.2). IMAGE

generates information on the total amounts of cropland and pasture for each of 26 world regions. If the IMAGE model estimate of the amount of cropland or pasture in a given region exceeds the total cropland or pasture area according to the GLOBIO land-use map, the latter is adjusted to accommodate the difference (the cropland or pasture 'claim'). This is done by distributing the cropland or pasture claim among the grid cells within the region, whereby allocation takes place according to decision rules based on the land use already present in the cells (for example, the cropland claim is preferentially allocated to grid cells that already contain cropland). Conversely, if the IMAGE estimates of cropland and pasture area are smaller than the estimates in the GLOBIO land-use map, the latter is adjusted by subtracting a proportion of cropland or pasture from each grid cell and replacing this by natural area, according to the proportions of natural land-cover classes present in that cell. If the cell does not contain natural land-cover classes, then the region- and biome-specific proportions of natural landcover classes are assigned. A more detailed explanation of the procedure to attune the GLOBIO land-use map to the cropland and pasture claims from the IMAGE model is provided in Appendix 1.

4) Once the cropland and pasture claims are allocated, the GLOBIO land-use classes are further subdivided according to land-use intensity or type. Cropland is subdivided into intensive agriculture, extensive agriculture, irrigated crops, and woody biofuels. Pastures are subdivided into man-made pastures and moderately to intensively used grasslands. Forest areas are subdivided into natural forest and four types of forestry: plantation, clear-cut forestry, selective logging and reduced impact logging (see Table 2.1, second column). For cropland, the subdivision is made based on information from the IMAGE model combined with information from Dixon *et al.* (2001), who provided data on the actual distribution of irrigated agriculture, intensive agriculture and extensive agriculture in various world regions. For pasture and forestry, the land-use differentiation is made based on IMAGE output only. Details of this procedure are provided in Appendix 2.

2.1.2 Past or future situations

The procedure for estimating past or future land use (i.e., land use for any year other than the baseline) is the same as the procedure for the baseline situation as described above, except that the land-use claims generated by the IMAGE model may change through time. Thus, for any given year, first the information on the GLC2000 map is aggregated to a grid cell size of 0.5^o by 0.5^o (step 1), then Eqs. 2.1 and 2.2 are applied (step 2), then the IMAGE claims for a given time step are allocated (step 3), and finally a further subdivision is made according to the land-use intensity (step 4). If the pasture or cropland claim from the IMAGE model for a given year is smaller than the pasture or cropland area in the baseline map, the agricultural land is replaced by natural area (see step 3 in section 2.1.1) and the original biodiversity (as expressed by MSA) is gradually restored. Further details on this procedure are provided in section 2.2.

Table 2.1 GLC2000 land-cover classes and corresponding GLOBIO land-use classes.

Land-cover category (GLC2000 classes) [a]	GLOBIO land-use class [b,c]	LU impact dominant? [d]
Forest (1-9)	Natural forest	NO
	Forestry - Plantation	NO
	Forestry - Clear-cut harvesting	NO
	Forest - Selective logging	NO
	Forest - Reduced impact logging	NO
Burnt forest (10)	Burnt forest	NO
Grassland (11,15)	Natural grassland	NO
Grassland (12-14)	Pasture (30) - moderately to intensively used	NO
	Pasture (30) - Man-made	NO
	Natural grassland	NO
Cropland (16)	Extensive cropland	YES
	Intensive cropland	YES
	Irrigated cropland	YES
	Woody biofuels	YES
Cropland/forest (17) [e]	*Distributed among cropland (16), pasture (30) and forest (17)*	NO
Cropland/natural vegetation (18) [e]	*Distributed among cropland (16), pasture (30) and natural grassland (18)*	NO
Bare areas (19)	Bare area	NO
Water bodies (20)	NA	-
Snow and ice (21)	Snow and ice	NO
Urban area (22)	Urban area	YES
Unknown (23) [e]	*Distributed among cropland (16) and pasture (30)*	-

[a] 1: Broad-leaved evergreen forest; 2: Closed broad-leaved deciduous forest; 3: Open broad-leaved deciduous forest; 4: Evergreen needle-leaved forest; 5: Deciduous needle-leaved forest; 6: Mixed leaf forest; 7: Regulary flooded forest, fresh water; 8: Regularly flooded forest, saline water; 9: Mosaic: forest/other natural vegetation; 10: Tree cover, burnt; 11: Evergreen closed-open scrubland; 12: Deciduous closed-open scrubland; 13: Herbaceous closed-open cover; 14: Sparse herbaceous or shrub cover; 15: Regularly flooded herbaceous or shrub cover; 16: Cultivated and managed areas; 17: Mosaic: cropland/forest/other natural vegetation; 18: Mosaic: cropland/shrub or grass cover; 19: Bare areas; 20: Water bodies; 21: Snow and ice; 22: Artificial surfaces and associated areas.

[b] Within GLOBIO, class 30 is added to the GLC2000 classification to represent the pasture calculated according to Eq. 2.2.

[c] Descriptions of the land-use classes are provided in Alkemade *et al.* (2009), Alkemade *et al.* (2013), Stehfest *et al.* (2014).

[d] If the land-use impact itself is domimant, no additional impacts are considered in the overall impact calculation. Else, the six impacts included in GLOBIO are assumed to interact multiplicatively (see Eq. 1.3).

[e] In GLOBIO, these GLC2000 classes are redistributed among pasture, cropland, forest and natural grassland, according to Eqs. 2.1 and 2.2.

2.2 Cause-effect relationships and impact calculation

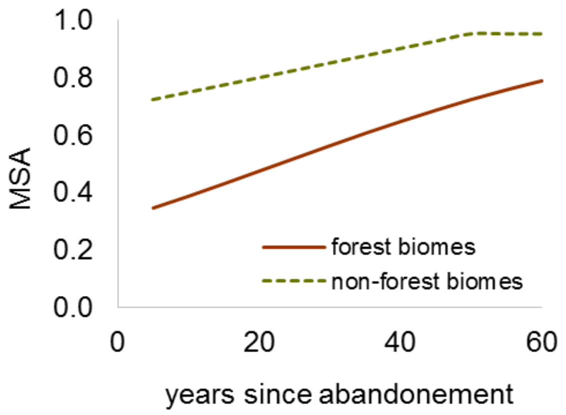
Relationships between MSA and land use have been quantified based on studies that reported species composition in a given type and intensity of land use as well as an undisturbed reference situation (Table 2.2). The impact of land use is calculated by assigning the MSA_{LU} values as shown in Table 2.2 to the proportions of the corresponding land-use classes present in each 0.5° x 0.5° grid cell. In case of abandoned agricultural land (cropland or pasture), the MSA value depends on the time that has passed since abandonment, as MSA will gradually increase due to succession and re-colonization processes. The increase of the MSA value over time since abandonment differs with biome type (Figure 2.1).

Table 2.2 MSA_{LU} values assigned to GLOBIO land-use classes. Sources: Alkemade *et al*. 2009; Alkemade *et al.* 2013; GLOBIO reference database (www.globio.info).

GLOBIO land-use class	MSA_{LU}
Forest - Natural	1.0
Forest - Plantation	0.30
Forest - Clear-cut harvesting	0.50[a]
Forest - Selective logging	0.70
Forest - Reduced impact logging	0.85
Burnt forest	1.0
Natural grassland	1.0
Pasture - moderately to intensively used	0.60
Pasture - man-made	0.30
Extensive cropland	0.30
Intensive cropland	0.10
Irrigated cropland	0.05
Woody biofuels	0.30
Bare area	1.0
Snow and ice	1.0
Urban area	0.05[b]

[a] Calculated as an average MSA for secondary vegetation over a varying number of years since clear-cut felling and/or land abandonment; [b] Value for densely populated cities without significant green space; based on expert judgement.

Figure 2.1 Recovery of MSA over time upon agricultural land abandonment, based on MSA values for secondary vegetation derived from studies with a varying number of years since forest clear-cut felling and/or land abandonment. Recovery pathways differ between forest biomes and other biomes. Biomes are derived from the IMAGE model (see Table A1).



3. Impacts of climate change

3.1 Global mean temperature change

Climate change affects MSA by causing shifts in the distribution ranges of species (Alkemade *et al.*, 2011). The pressure is included in GLOBIO 3.5 using the global mean temperature increase (GMTI, in °C), as simulated with the IMAGE model.

3.2 Cause-effect relationships

Effects of climate change are quantified as losses in MSA per degree of global mean temperature increase ($MSA_{loss} \cdot {}^{o}C^{-1}$) for 14 terrestrial biomes (Table 3.1). The cause-effect relationships are based on a meta-analysis of studies that quantified the influence of climate change on the distributions of plant and/or vertebrate species. These studies used climate envelope models to estimate range shifts of many species in relation to projected future climate change, from which information was derived on the fraction of remaining species (FRS) relative to the original species richness at a given location (Arets *et al.*, 2014). The FRS were then related to global mean temperature changes corresponding with the climate scenarios of concern. The FRS equals MSA under the assumption that outside the climate envelope of a species the abundance of that species is zero and that within the climate envelope the abundance of a species is not related to climate.

Table 3.1 Cause-effect relationships expressing the loss in MSA ($1-MSA_{CC}$) in relation to global mean temperature increase in °C (Arets *et al.*, 2014).

Biome	$MSA_{loss} \cdot {}^{o}C^{-1}$	SE	*p*-level	N
Boreal forest	0.0367	0.0125	0.005	48
Cool coniferous forest	0.1127	0.007	<0.001	15
Grassland and steppe	0.1201	0.023	<0.001	22
Hot desert	0.1201 [a]	-	-	-
Ice	0.0356	0.004	<0.001	8
Mediterranean shrub	0.0661 [b]	-	-	-
Savanna	0.0775	0.0104	<0.001	12
Scrubland	0.0661	0.0072	<0.0001	28
Temperate deciduous forest	0.071	0.008	<0.001	18
Temperate mixed forest	0.0487	0.0066	<0.001	18
Tropical forest	0.1075 [c]	-	-	-
Tropical woodland	0.1075	0.0128	<0.0001	39
Tundra	0.0426	0.0045	<0.001	8
Warm mixed forest	0.1457	0.0122	<0.0001	17
Wooded tundra	0.0426 [d]	-	-	-

[a] set equal to the MSA loss factor for grassland and steppe; [b] set equal to the MSA loss factor for scrubland; [c] set equal to the MSA loss factor for tropical woodland; [d] set equal to the MSA loss factor for tundra

3.3 Impact calculation

The MSA in relation to climate change is calculated by combining the global mean temperature increase (GMTI, in °C) with the global distribution of biomes and the relationships between MSA_{CC} and GMTI (Table 3.1). The GMTI and the map with biomes for a given time step are derived from the IMAGE model. To account for the delay in species response to temperature change, a delay factor of 2 is applied to the cause-effect relationships that were reported by Arets *et al.* (2014). In practice, this means that the $MSA_{loss} \cdot {}^{o}C^{-1}$ is considered to be a factor of 2 lower compared to the numbers reported in Table 3.1. For instance, the impact in grassland and steppe is considered to be 0.06 $MSA_{loss} \cdot {}^{o}C^{-1}$ instead of 0.12 $MSA_{loss} \cdot {}^{o}C^{-1}$. Next, the biome-specific climate impacts are applied to the GLOBIO land-use map, whereby it is assumed that the direct land-use effects of cropland and urban area take precedence over the effects of climate change (see Table 2.1). Thus, the MSA for climate change is assigned only to the GLOBIO land-use classes other than cropland and urban area.

4. Impacts of nitrogen deposition

4.1 Atmospheric nitrogen deposition

Adverse effects of atmospheric nitrogen deposition on ecosystems become apparent only after the assimilative capacity of the ecosystem is exceeded (Bouwman *et al.*, 2002, Stehfest *et al.*, 2014). The level at which this occurs, is called the critical load. In GLOBIO, adverse effects of atmospheric nitrogen deposition on MSA are calculated based on the deposition in excess of the critical load (N exceedance; N_E):

$$N_E = N_D - N_{CL} \qquad \text{(Eq. 4.1)}$$

where N_E represents the nitrogen deposition in exceedance of the critical load, N_D represents the nitrogen deposition and N_{CL} is the nitrogen critical load (all expressed in $g \cdot m^{-2} \cdot yr^{-1}$) Present and future levels of nitrogen deposition are derived from the IMAGE model, at a 0.5° by 0.5° resolution. Critical loads have been calculated by Bouwman *et al*. (2002).

4.2 Cause-effect relationships

Cause-effect relationships for nitrogen deposition were derived from studies that experimentally assessed the effects of nitrogen addition on local plant species richness (i.e., in this case local plant species richness is considered a proxy for MSA). Observations were divided among forests, grasslands and Arctic alpine ecosystems, which were linked to the GLC2000 classes forest (1-10), grassland (11-15) and snow and ice (20), respectively (Table 4.1).

Table 4.1 Cause-effect relationships describing the MSA due to nitrogen deposition in excess of the critical load (i.e., N_E in $g \cdot m^{-2} \cdot yr^{-1}$; see Eq. 4.1). Relationships were derived from Bobbink *et al.* (2010) and have been previously published in Alkemade *et al.* (2009).

Cause-effect relationship	R^2	*p*-level	N	GLC2000 classes
$MSA_N = 1 - 0.220 \ln (N_E + 1)$	0.81	< 0.01	9	Forests (1, 2, 3, 4, 5, 6, 7, 8, 9, 10)
$MSA_N = 1 - 0.189 \ln (N_E + 1)$	0.96	< 0.01	12	Grasslands (11, 12, 13, 14, 15)
$MSA_N = 1 - 0.145 \ln (N_E + 1)$	0.85	< 0.01	21	Snow and ice (20)

4.3 Impact calculation

The MSA due to atmospheric nitrogen deposition is calculated by combining the map with the excess nitrogen deposition (N_E in $g \cdot m^{-2} \cdot yr^{-1}$) with the cause-effect relationships that quantify the response of MSA_N to N_E (Table 4.1). It is assumed that the direct land-use effects of cropland and urban area take precedence over the effects of atmospheric nitrogen deposition. Therefore, the cause-effect relationships for atmospheric nitrogen deposition are applied only to land-use classes other than cropland and urban area (see Table 2.1).

5. Impacts of infrastructure

5.1 Infrastructure maps

Infrastructure affects MSA both via habitat fragmentation (see chapter 6) and via disturbance of the surrounding natural habitat (Benítez-López *et al.*, 2010). In GLOBIO, the main source of the present-day infrastructure is the database from the Global Roads Inventory Project (GRIP). This database provides a vector-format road map compiled from a variety of land- or region-specific road inventory data. The GRIP dataset distinguishes five types of roads: highways (type 1), primary roads (type 2), secondary roads (type 3), tertiary roads (type 4) and urban/residential roads (type 5). A more extensive description of the GRIP dataset is provided in a forthcoming paper (Meijer *et al.,* in prep). Data on the locations of other infrastructural elements (railways, power and utility lines, mining locations) are derived from the Digital Chart of the World (DCW) (1992).

5.2 Calculation of the infrastructure impact zone

5.2.1 Baseline situation (reference year 2000)

Infrastructure disturbance in terms of MSA is largest in the direct vicinity of the infrastructure and shows a steep decrease with increasing distance (Benítez-López *et al.*, 2010). In GLOBIO, it is assumed that disturbance by infrastructure is confined to an impact zone of 1 km around infrastructural elements. To map the infrastructure impact zone, first the road map from the GRIP database (including all road types 1-5) is combined with the DCW map (see above). Next, a 1 km impact zone is delineated around the infrastructure. This impact zone map (vector format) is then converted to a raster map on a 1 by 1 km resolution, and this rasterized impact zone map is used to calculate the total area of the infrastructure impact zone (km^2) per 0.5° by 0.5° grid cell.

5.2.2 Future situations

The future dimensions of the infrastructure impact zone (in km^2 per 0.5° by 0.5° grid cell) are expected to change as a function of human population density, land-use intensity, the presence of protected areas and the distance to the coast. Per 0.5° by 0.5° grid cell, the total area of the infrastructure impact zone in a given year *j* is calculated as a function of the situation in the baseline year 2000 and a cell-specific growth factor, as follows:

$$RIZ_{i,j} = (1 + (GF_{i,0}/100))^{((j*2)-10)} * RIZ_{i,2000} \quad \text{(Eq. 5.1)}$$

where $RIZ_{i,j}$ is the infrastructure impact zone (km^2) in cell *i* in year *j* and $GF_{i,0}$ is the growth factor (1/year) for cell *i* in the reference year (i.e., year 2000), which is calculated as:

$$GF_{i,0} = GF_{PD,i,0} * GF_{LC,i,0} * GF_{PA,i,0} * GD_{DC,i,0} \quad \text{(Eq. 5.2)}$$

where GF represents the growth factor, PD represents human population density, LC represents land cover, PA represents protected area and DC represents distance to coast. The growth factor for population density is set to 0.5, 1.0, and 1.5 for human population densities <10, between 10 and 50, and >50 individuals/km², respectively. The land-cover growth factor is based on the IMAGE global land-cover type that the infrastructure is located in (Table 5.1). The growth factor for the protected areas is based on the proportion of protected area within each cell, as calculated in the GLOBIO land-use map (see section 2.1.1). The higher the proportion of protected area in a cell, the lower the road impact growth factor (Table 5.2), assuming that future infrastructure developments will preferentially take place outside protected areas. The growth factor for the distance to the coast has a value of 1.25 for areas within a distance of 50 km from the coast and a value of 1.00 for all other cells.

Table 5.1 Infrastructure impact zone growth factor per IMAGE global land-cover type (GLCT).

ID	IMAGE GLCT	Road impact zone growth factor
Non-natural		
1	agricultural land	1.00
2	extensive grassland	0.75
3	regrowth forest abandonment	1.25
4	carbon plantation	0.75
5	regrowth forest timber	1.00
6	biofuels	1.00
Natural ('biomes')		
7	ice	0.25
8	tundra	0.75
9	wooded tundra	1.00
10	boreal forest	1.25
11	cool coniferous forest	1.25
12	temperate mixed forest	1.75
13	temperate deciduous forest	1.75
14	warm mixed forest	1.75
15	grassland and steppe	0.75
16	hot desert	0.50
17	scrubland	0.75
18	savannah	0.75
19	tropical woodland	1.00
20	tropical forest	1.75
21	Mediterranean vegetation	1.00

Table 5.2 Infrastructure impact zone growth factor in relation to the proportion of protected area within a grid cell.

Proportion of protected area	Road impact zone growth factor
0	1.00
0 – 0.10	0.67
0.1 – 0.25	0.50
0.25 – 0.50	0.40
0.50 – 1.0	0.33

5.3 Cause-effect relationships

The relationship between MSA and infrastructure is quantified based on a meta-analysis from Benítez-López *et al.* (2010). They quantified the MSA of birds and mammals in relation to distance from roads and found lower MSA values in the proximity of roads. Based on the results of their study, an average MSA of 0.66 for birds and mammals has been quantified for the 1 km impact zone. As it is assumed that infrastructure proximity affects other terrestrial vertebrates as well (Table 1.1), the overall MSA_I for the 1 km impact zone has been quantified as $4/6 \cdot 0.66 + 2/6 \cdot 1 = 0.78$.

Table 5.3 Priorities for assigning infrastructure impacted areas to GLC2000 land-cover classes within the GLOBIO model. PA = protected area; NA = not applicable.

GLC2000 class		Infra-priority		Natural
ID	**Description**	**No PA**	**PA**	**habitat?**
22	Artificial surfaces and associated areas	1	24	NO
16	Cultivated and managed areas	2	2	NO
17	Mosaic: Cropland / Tree Cover	3	3	YES
18	Mosaic: Cropland / Other natural vegetation	4	4	YES
30	Pasture	5	NA	YES
10	Tree Cover, burnt	6	25	YES
20	Water Bodies (natural & artificial)	7	26	YES
19	Bare Areas	8	27	YES
13	Herbaceous Cover, closed-open	9	28	YES
12	Shrub Cover, closed-open, deciduous	10	29	YES
11	Shrub Cover, closed-open, evergreen	11	30	YES
14	Sparse Herbaceous or sparse shrub cover	12	31	YES
15	Regularly flooded shrub and/or herbaceous cover	13	32	YES
9	Mosaic: Tree cover / Other natural vegetation	14	33	YES
3	Tree Cover, broadleaved, deciduous, open	15	34	YES
2	Tree Cover, broadleaved, deciduous, closed	16	35	YES
8	Tree Cover, regularly flooded, saline, (daily variation)	17	36	YES
7	Tree Cover, regularly flooded, fresh	18	37	YES
6	Tree Cover, mixed leaf type	19	38	YES
5	Tree Cover, needle-leaved, deciduous	20	39	YES
4	Tree Cover, needle-leaved, evergreen	21	40	YES
1	Tree Cover, broadleaved, evergreen	22	41	YES
21	Snow and Ice (natural & artificial)	23	42	YES
23	Unknown	99	99	YES

5.4 Impact calculation

Based on a land-cover class prioritization (Table 5.3), the total area of the infrastructure impact zone per grid cell (see section 5.2) is distributed among the land-cover proportions within the 0.5° by 0.5° grid cell until the total impacted area is allocated. As an example: assume that a certain grid cell has a total area of 1000 km^2, consisting of 50 km^2 of urban area, 500 km^2 of cropland and 450 km^2 of broadleaved deciduous forest. Assume further that the total area of the infrastructure impact zone is 700 km^2. Using the priorities from Table 5.3, the first 50 km^2 of the impacted area is then assigned to urban area (class 22; priority

1), the next 500 km^2 to cropland (class 16; priority 2), and the remaining 150 km^2 is assigned to broadleaved deciduous forest (class 3; priority 15). This leaves no direct infrastructure impact for the remaining 300 km^2 of forest area. As it is assumed that infrastructure causes no (additional) MSA loss in urban areas and cropland (see Table 2.1), the MSA_I value of 0.78 is then assigned only to the 150 km^2 of impacted forest area. This implies that the 450 km^2 of forest within that grid cell gets an MSA_I value of $1-(150/450 \cdot (1-0.78)) = 0.93$.

In the impact calculation, it is assumed that infrastructure impacts are lower in protected areas as compared to unprotected areas, because of targeted spatial planning and regulation measures. For example, it is assumed that roads are preferentially constructed outside of protected areas, or that traffic within protected areas is restricted. Therefore, in protected areas the MSA_I value of 0.78 is replaced by $MSA_I = 0.90$.

6. Impacts of habitat fragmentation

6.1 Infrastructure map

It is assumed that habitat fragmentation is primarily caused by main roads (highways, primary roads and secondary roads) and that other infrastructural elements do not significantly contribute to fragmentation. The infrastructure map to quantify fragmentation is therefore compiled by selecting road types 1-3 from the GRIP database (section 5.1). This vector-format map is then converted to a 1 by 1 km binary raster map (road or not), in order to facilitate overlaying with the raster-based land-use map.

6.2 Defining habitat fragments

To define the habitat fragments, first an overlay is made of the 1 by 1 km road map and the GLC2000 land-cover map. This overlay defines the maximum size of each patch as defined by the roads (i.e., without further fragmentation by land use). These maximum patch sizes are summarized at a 0.5° by 0.5° resolution grid by storing the patch identification number and its total size as attributes of the corresponding grid cell. In a next step, the patch sizes are adjusted to account for fragmentation by land use (cropland and urban area). To that end, the GLOBIO land-use map (section 2.1) is reclassified into two main classes: man-made land (classes 16 and 22) and other land-cover (all other classes, hereafter referred to as 'natural' habitat). Then, the size of each patch as delineated by the roads is adjusted to represent the area of natural habitat only.

Table 6.1 Relationship between MSA_F values and the patch size of natural habitat.

Patch area (km^2)	MSA_F
0 – 1	0.35
1 – 10	0.45
10 – 100	0.65
100 – 1000	0.90
1000 – 10000	0.98
> 10000	1.00

6.3 Cause-effect relationships and impact calculation

To quantify the cause-effect relationship for habitat fragmentation, a literature review was performed to collect species-specific empirical data on the minimum viable population sizes (MVP) of birds and mammals (Verboom *et al.*, 2014). These MVP estimates obtained were converted to minimum area requirements (MAR) using data on individual home range sizes (for the 36 bird species included) or typical population densities (for the 80 mammal species). The cumulative distribution of MAR values was then used to estimate the proportion of species for which the MAR was met as a function of the available habitat area (Verboom *et al.*, 2014). For implementation in GLOBIO, these results were translated into a categorical classification of patch areas and corresponding MSA values (Table 6.1). The values shown in the table are assumed to hold for all six taxononic groups, in orther words, they have been corrected for the assumption that invertebrates and plants are not impacted by fragmentation (see Table 1.1). To quantify the impact of fragmentation, the MSA_F values as shown in Table 6.1 are assigned to the patches of natural habitat within each 0.5° x 0.5° grid cell, based on the total patch size.

7. Impacts of human encroachment

7.1 Human access points

Human encroachment comprises anthropogenic activities in otherwise natural areas. Examples include hunting, gathering of food or fuel (wood), and recreation and tourism. Human settlements, roads and river networks (with villages located along the last two) are the major access points to natural areas, and are assumed to be represented by urban areas and cropland in the GLOBIO land-use map. It is further assumed that encroachment takes place within a 10 km zone around cropland and urban areas.

7.2 Cause-effect relationships

Based on a review of studies that quantified bird and mammal abundance in relation to hunting pressure in the proximity of settlements, an MSA of 0.56 has been quantified for the 10 km impact zone (Benítez-López *et al.*, unpublished data). It is assumed that human encroachment affects mammals and birds (Table 1.1), notably through habitat disturbance and hunting. The MSA over the six taxonomic groups is therefore calculated as $2/6 \cdot 0.56 + 4/6 \cdot 1 = 0.85$.

7.3 Impact calculation

Based on model simulations with hypothetical 0.5° by 0.5° grid cells consisting of different configurations and proportions of cropland and urban land use, it was estimated that a proportion of cropland and urban area of 1.5% is sufficient to have the entire 0.5° by 0.5° grid cell influenced by human encroachment. The procedure followed to identify this 1.5% threshold is further explained in Appendix 3. Based on the threshold combined with information on the proportions of cropland or urban area, as derived from the land-use map, each grid cell is classified as one of three encroachment types:

- cells with more than 1.5% of cropland or urban area (type 1);
- cells with containing between 0 and 1.5% cropland or urban area (type 2);
- cells without cropland or urban area, yet located within 10 km of cells that do contain cropland or urban area (type 3).

However, in a geographic projection the cell dimensions vary with latitude, which implies that cells at higher latitude are increasingly likely to be influenced by human encroachment from access points (cropland and urban area) in their neigbouring cells. The procedure that has been developed to accommodate the differences in cell area in the identification of the cell types 1-3 is explained in more detail in Appendix 4.

After each cell has been assigned to type 1, 2 or 3, the impact of human encroachment is calculated based on the generic MSA_E value of 0.85 (see section 8.2) combined with a cell-specific correction factor, as follows (Eqs. 7.1 - 7.3):

Type 1 $$\mathrm{MSA}_{E,i} = \mathrm{MSA}_E \qquad \text{(Eq. 7.1)}$$

Type 2 $$\mathrm{MSA}_{E,i} = 1 - (\frac{P_{crop,urban}}{0.015} * (1 - \mathrm{MSA}_E)) \quad \text{(Eq. 7.2)}$$

Type 3 $$\mathrm{MSA}_{E,i} = 1 - (\frac{1}{3} * (1 - \mathrm{MSA}_E)) \quad \text{(Eq. 7.3)}$$

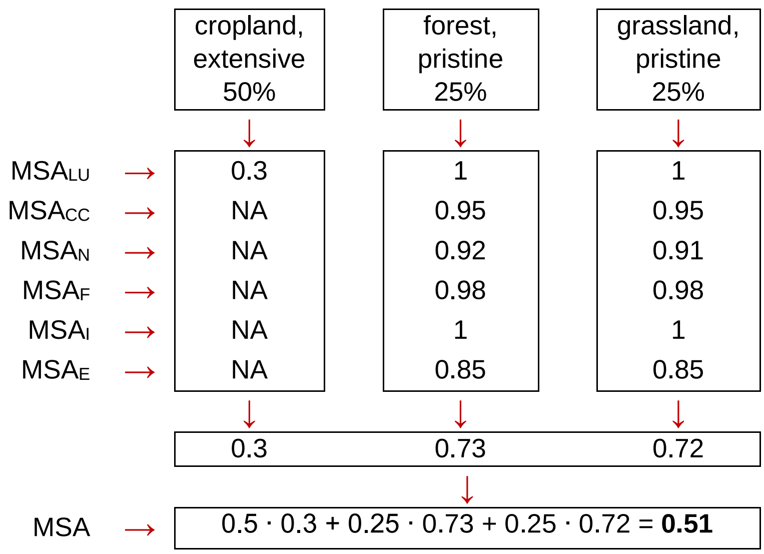
where $MSA_{E,i}$ is the MSA in cell *i*, $P_{crop,urban}$ is the proportion of cropland and urban area, and MSA_E is the generic value for MSA due to encroachment (i.e., 0.85). Once the cell-specific $MSA_{E,i}$ values are calculated, they are applied to all land-use types other than cropland and urban area, with the exception of areas that are protected. It is assumed that in protected areas, encroachment is strongly limited due to targeted conservation and management measures. Therefore, MSA_E is set to 1 in protected areas.

8. Aggregating MSA values

8.1 Aggregation across impacts

In the end, the MSA values in relation to the different impacts are aggregated per grid cel, based on the proportional distribution of areas that are homogeneous with respect to the different impacts. Suppose we have a hypothetical 0.5° by 0.5° grid cell close to the equator (~ 50 by 50 km), located in the tropical forest biome, and consisting of 50% extensive cropland, 25% natural grassland and 25% pristine forest (so, 50% man-made and 50% natural habitat). Assume further that the natural habitat is part of a larger patch that measures 6000 km^2 in total (i.e., the patch extends beyond the cell). Finally, assume for this cell an excess atmospheric nitrogen deposition of 5 $kg{\cdot}ha{\cdot}yr^{-1}$ (i.e., 0.5 $g{\cdot}m^{-2}{\cdot}yr^{-1}$) and a global mean temperature increase of 1°C. Thus, the cell consists of three parts that are homogenous with respect to the different impacts (Figure 8.1).

Figure 8.1 Integration of the different MSA values in a hypothetical 0.5° by 0.5° grid cell located in the IMAGE biome 'tropical forest'. NA = not applicable.



As the direct land-use impact of cropland is dominant over the others, only MSA_{LU} is considered for the cropland part. The pristine forest and grassland parts are unaffected by direct land-use impact (MSA_{LU} =1). The MSA values for climate change for the pristine forest and grassland are calculated as 1 minus the MSA_{loss} corresponding with 1°C increase in global mean temperature for tropical forest, divided by a correction factor of 2 (i.e., MSA_{CC} = 1 - 0.1075/2, see chapter 2). The forest and grassland parts are further subjected to atmospheric nitrogen deposition, resulting in MSA_N = 0.92 and MSA_N = 0.91 for forest and grassland, respectively (according to the regression equations in Table 4.1). The MSA due to fragmentation is calculated by assigning an MSA_F value to the forest and grasland that corresponds with the size of the encompassing patch (Table 6.1). Finally, the entire cell is assumed to be subject to human encroachment (> 1.5%

cropland, Eq. 7.1), hence a generic MSA_E of 0.85 is assigned to both the forest and grassland patches.

In the end, the overall MSA values are aggregated over the different parts of the grid cell as an area-weighted average, in order to come to a single overall MSA estimate for the grid cell.

8.2 Aggregation across regions

MSA values can be aggregated to larger regions or countries by calculating an area-weighted mean over the MSA values of the grid cells within the region or country, as

$$MSA_r = \sum_{i=1}^{i=n} \left(MSA_i \cdot A_i / \sum_{i=1}^{i=n} A_i \right)$$

(Eq. 8.1)

where MSA_r is the overall MSA of the region, MSA_i is the MSA of grid cell *i* and A_i is the surface area of grid cell *i*.

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APPENDIX 1

Allocation of cropland and pasture claims from the IMAGE model

The IMAGE model produces two types of land-use data: a map with so-called global land-cover types (GLCTs), which includes agricultural land use (see Table A1), and the proportions of different crop types for each IMAGE region (including grass/fodder, various rainfed crops, various irrigated crops and various biofuel crops; see Table A2 for an overview of the crop types and Table A3 for an overview of the IMAGE regions). The procedure to match the proportions of cropland and pasture in the GLOBIO land-use map with the IMAGE land-use data is described below.

Cropland

First, the total area of cropland per IMAGE region, represented by the sum of all crops except fodder (crop 1) and non-woody biofuels (crop 12) (Table A2), is compared with the region-specific total area of cropland in the initial GLOBIO land-use map (i.e., the area as estimated with Eq. 2.1 and aggregated with Eq. 8.1). If the IMAGE estimate is larger than the estimate in the initial GLOBIO map, then the difference (the cropland 'claim') is redistributed among the grid cells within the region, in the following sequence:

1) Allocate cropland to non-forest GLC2000 classes in cells that already contain cropland. Bare areas (GLC200 class 19), water bodies (20), snow and ice (21) and artificial surfaces (22) are excluded, hence allocation takes place in GLC2000 classes 11-18.
2) Allocate the remainder to non-forest GLC2000 classes in grid cells that are classified as agricultural land in IMAGE (GLCT 1). Again, bare areas (GLC200 class 19), water bodies (20), snow and ice (21) and artificial surfaces (22) are excluded, hence allocation takes place in GLC2000 classes 11-18.
3) Allocate the remainder to forest (GLC2000 classes 1-9) in grid cells that already contain cropland.
4) Allocate the remainder to forest (GLC2000 classes 1-9) in grid cells classified as agricultural land in IMAGE (GLCT 1).
5) Allocate the remainder to forest (GLC2000 classes 1-9) in grid cells classified as GLCTs other than agricultural land (i.e., no GLCT 1), but exclude ice, tundra and wooded tundra (IMAGE GLCTs 7-9; see Table A1).

If in a region the total cropland area estimate from IMAGE is smaller than the total cropland area in the initial GLOBIO land-use map, the proportions of cropland per grid cell are lowered by a factor that represents the difference between the claim and the estimated total cropland area, as follows:

$$P_{cropland,c} = P_{cropland,o} \cdot \frac{\sum_i Area_{cropland,i,j}}{Claim_{cropland,j}} \quad \text{(Eq. A1)}$$

where P_c and P_o are the corrected and original proportions of cropland, $Area_{cropland,i,j}$ is the cropland area in cell i for IMAGE region j as estimated in the initial GLOBIO land-use map, and $Claim_{cropland,j}$ is the total cropland claim for region j according to the IMAGE model. The difference between P_c and P_o, which represents 'vacant' area, is then allocated to natural land cover. If there are natural land-cover classes present within the grid cell, the vacant area per cell is proportionally allocated to these natural classes (excluding bare areas (class 19) and snow and ice (class 21)). If the cell consists only of man-made classes (cropland (class 16) and urban area (class 22)), bare areas (class 19) or snow and ice (class 21), then the region- and biome-specific proportions of natural landcover classes are assigned.

Pasture

First, the total area of pasture per IMAGE region (the pasture 'claim') is calculated as the area with grass/fodder (IMAGE crop type 1; see Table A2) minus the area of extensive grassland (IMAGE GLCT 2; see Table A1). This pasture claim is compared with the total area of pasture in the initial GLOBIO map, as obtained with Eq. 2.2 (i.e., the total area of the new land-use class 30). If the IMAGE estimate is larger, then the difference (pasture 'claim') is allocated to grid cells within the region, in the following sequence:

1) Allocate pasture to non-forest GLC2000 classes in those cells that already contain pasture or crop. Bare areas (GLC200 class 19), water bodies (20), snow and ice (21) and artificial surfaces (22) are excluded, hence allocation takes place in GLC2000 classes 11-18.
2) Allocate the remainder to non-forest GLC2000 classes in grid cells that are classified as agricultural land in IMAGE (GLCT 1). Again, bare areas (GLC200 class 19), water bodies (20), snow and ice (21) and artificial surfaces (22) are excluded, hence allocation takes place in GLC2000 classes 11-18.
3) Allocate the remainder to forest (GLC2000 classes 1-9) in those cells that already contain pasture or crop.
4) Allocate the remainder to forest (GLC2000 classes 1-9) in grid cells classified as agricultural land or extensive grassland in IMAGE (GLCT 1 or GLCT 2).
5) Allocate the remainder to forest (GLC2000 classes 1-9) in grid cells classified as GLCTs other than agricultural land or extensive grassland in IMAGE (i.e., no GLCT 1 or GLCT 2), but exclude ice, tundra and wooded tundra (IMAGE GLCTs 7-9; see Table A1).

If in a region the total pasture area as estimate by IMAGE is smaller than the total area of the new GLC2000 class 30 in the initial GLOBIO land-use map, the proportions of pasture are lowered by a factor that represents the difference between the claim and the estimated total pasture area, similar to the procedure for cropland as described above.

Table A1 Global land-cover types (GLCTs) generated by the IMAGE model.

ID	IMAGE GLCT	Forest biome?
	Non-natural	
1	agricultural land	-
2	extensive grassland	-
3	regrowth forest abandonment	-
4	carbon plantation	-
5	regrowth forest timber	-
6	biofuels	-
	Natural ('biomes')	
7	ice	no
8	tundra	no
9	wooded tundra	no
10	boreal forest	yes
11	cool coniferous forest	yes
12	temperate mixed forest	yes
13	temperate deciduous forest	yes
14	warm mixed forest	yes
15	grassland and steppe	no
16	hot desert	no
17	scrubland	no
18	savannah	no
19	tropical woodland	yes
20	tropical forest	yes
21	Mediterranean vegetation	no

Table A2 IMAGE crop types.

ID	Crop type
1	grass/fodder
	rainfed crops
2	temperate cereals
3	rice
4	maize
5	tropical cereals
6	pulses
7	roots & tubers
8	oil crops
	biofuel crops
9	sugar cane
10	maize
11	woody biofuels
12	non-woody biofuels
	irrigated crops
13	temperate cereals
14	rice
15	maize
16	tropical cereals
17	pulses
18	roots & tubers
19	oil crops

APPENDIX 2

Land-use differentiation according to land-use intensity

Cropland

Cropland is divided into irrigated cropland, intensive cropland and extensive cropland. The proportions of these different cropland intensity classes are first calculated per IMAGE region and then allocated to the 0.5° by 0.5° grid cells of the GLOBIO land-use map.

The amount of irrigated cropland per IMAGE region is directly derived from the IMAGE model (crop types 13-19; see Table A2). The IMAGE model does not provide output on the amounts of intensive and extensive cropland, but provides a so-called 'management factor' (MF) for all cropland, including irrigated crops, to indicate intensity (i.e, the ratio between actual and potential yields). In the GLOBIO model, the mean MF per IMAGE region is translated into proportions of extensive and extensive cropland. Using the proportions of irrigated cropland, intensive cropland and extensive cropland as reported by Dixon *et al. (2001)* for various world regions for the year 2000 (see Table A3), first a region-specific MSA value for cropland was calculated for the baseline year 2000, as

$$MSA_{crop,2000} = A_{irr,2000} \cdot MSA_{irr} + A_{int,2000} \cdot MSA_{int} + A_{ext,2000} \cdot MSA_{ext} \qquad \text{(Eq. A2)}$$

where MSA_{crop} is a region-specific MSA value aggregated over the three cropland types, A_{irr}, A_{int} and A_{ext} are the IMAGE regional totals of irrigated, intensive and extensive cropland and MSA_{irr}, MSA_{int} and MSA_{ext} are the MSA values of these different cropland intensity classes, i.e., 0.05, 0.1 and 0.3, respectively (see Table 2.2). MSA_{crop} can be considered an indicator of cropland use intensity. Therefore, a relationship between MSA_{crop} and the MF from IMAGE was established by relating $MSA_{crop,2000}$ to the region-specific mean MF values for the year 2000, resulting in the following power function (see also Figure A1):

$$MSA_{crop,mf} = 0.0972 \cdot MF^{-0.618} \qquad \text{(Eq. A3)}$$

Now, for any region and given year *j*, the amount of intensive cropland is calculated by simultaneously solving Eqs. A4 and A5 for $A_{int,j}$:

$$A_{crop,j} = A_{irr,j} + A_{int,j} + A_{ext,j} \qquad \text{(Eq. A4)}$$

$$A_{crop,j} \cdot MSA_{crop,j} = A_{irr,j} \cdot MSA_{irr} + A_{int,j} \cdot MSA_{int} + A_{ext,j} \cdot MSA_{ext} \qquad \text{(Eq. A5)}$$

which gives

$$A_{int,j} = (A_{crop,j} \cdot MSA_{crop,j} - A_{irr,j} \cdot MSA_{irr} - A_{crop,j} \cdot MSA_{ext} + A_{irr,j} \cdot MSA_{ext})/(MSA_{int} - MSA_{ext}) \qquad \text{(Eq. A6)}$$

whereby $A_{crop,j}$ and $A_{irr,j}$ are derived from the IMAGE model and $MSA_{crop,j}$ is calculated as

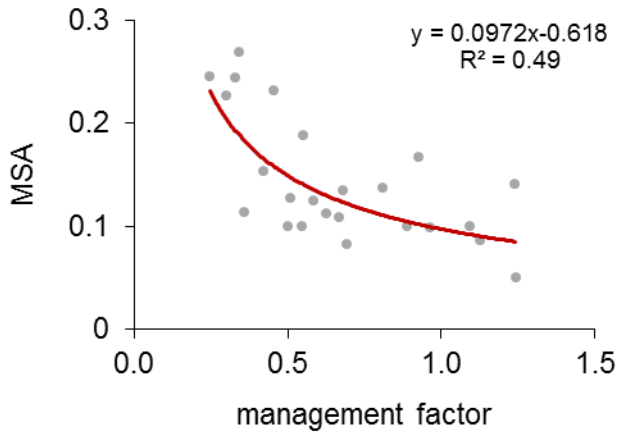
$$MSA_{crop,j} = MSA_{crop,2000} - (MSA_{crop,mf,2000} - MSA_{crop,mf,j}) \qquad \text{(Eq. A7)}$$

So, for any region and given year j, a value $MSA_{crop,mf,j}$ is derived from the MF for that region and that year using Eq. A3, and then the difference between $MSA_{crop,mf,j}$ and $MSA_{crop,2000}$ is used to assess $MSA_{crop,j}$. $MSA_{crop,j}$ has a minimum of 0 and a maximum of $MSA_{crop,j} = ((A_{crop,j} - A_{irr,j}) \cdot MSA_{ext} + A_{irr,j} \cdot MSA_{irr})/A_{crop,j}$.

The area of intensive cropland ($A_{int,j}$), as derived from Eq. A6, is then compared with the total cropland area and the irrigated cropland area (both derived from IMAGE). If $A_{int,j} > A_{crop,j} - A_{irr,j}$, then $A_{int,j} = A_{crop,j} - A_{irr,j}$ (in other words, then there is no extensive cropland). Finally, the area of extensive cropland is calculated as $A_{ext,j} = A_{crop,j} - A_{irr,j} - A_{int,j}$.

In the end, the regional totals of intensive, extensive and irrigated cropland are combined with the regional total of woody biofuels (which is directly derived from IMAGE, i.e., crop type 11 (see Table A2)), in order to calculate the proportions of these four cropland types per IMAGE region. These proportions are then allocated to the cropland in the 0.5° by 0.5° grid cells in the GLOBIO land-use map. Cropland within protected areas is always considered extensive cropland. The remaining extensive cropland as well as the proportions of the other three cropland types are proportionally assigned to the remaining cropland area within the region.

Figure A1 Relationship between MSA for cropland and management factor (R^2 = 0.49). Each observation represents an IMAGE region with corresponding MF for the year 2000. Corresponding region-specific MSA values for cropland were calculated based on the region-specific proportions of irrigated agriculture, extensive agriculture and intensive agriculture as reported by Dixon *et al.* (2001), combined with MSA values of 0.05 for irrigated cropland, 0.1 for intensive cropland, and 0.3 for extensive cropland (see Table 2.2).



Pasture

Pastures are subdivided into man-made pastures and moderately to intensely used grasslands (Table 2.1), based on the IMAGE biome map. If a grid cell with pasture is within one of the five forest biomes (Cool coniferous forest, Temperate mixed forest, Temperate deciduous forest, Warm mixed forest, Tropical forest; see Table A1), then it is considered 'man-made pasture', assuming that grassland within forest is anthropogenic by definition. If the grid cell is in another biome, the pasture is considered moderately to intensely used grassland.

Forestry

Forest areas are subdivided into natural forest and various types of forestry. Per IMAGE region, the IMAGE model reports the total area of three forestry types (plantation, clear-cut forestry and selective logging). A fourth forestry type (reduced impact logging) is calculated as a percentage of the selective logging (Arets *et al.*, 2011). Per IMAGE region, first the total forestry area reported by IMAGE is subtracted from the total forest area according to the GLOBIO land-use map. This difference represents the area of natural forest per IMAGE region. Next, the total area of the five different forest types per IMAGE region (i.e., four forestry types + natural forest) is distributed among the grid cells with forest within that region. Natural forest is preferentially allocated to protected areas. The remaining natural forest as well as the area of the four forestry types is then proportionally assigned to the remaining (unprotected) forest within the region. For example, suppose that the total amount of forest in a given IMAGE region consists of 40% natural forest, 20% forest plantation and 40% selective logging. Assume further that 20% of the total amount of forest in a given grid cell is protected. Then half of the natural forest in that cell (i.e., 20% of the total) as estimated by IMAGE is considered protected area. The remaining 80% is proportionally assigned to the rest of the forest in that cell, so 25% of natural forest, 25% of forest plantation and 25% of selective logging. If the protected forest area is larger than the area of natural forest, then it is assumed that selective logging takes place in the protected area.

Table A3 Proportional distribution of agricultural intensity classes per IMAGE region for the year 2000, derived from data reported by Dixon *et al*. (2001). The regions considered by Dixon *et al.* (2001) were sub-Saharan Africa, North Africa, Middle East, East Europe, Central Asia, South Asia, East Asia, the Pacific, Latin America and the Caribbean. In regions not covered by Dixon *et al.* (2001), 100% intensive cropland was assumed, except for Western Europe, where 100% irrigated cropland was assumed.

IMAGE region		Proportions of different cropland types		
		irrigated	intensive	extensive
1	Canada	0	1	0
2	USA	0	1	0
3	Mexico	0.45	0.26	0.30
4	Central America	0.21	0.59	0.19
5	Brazil	0.04	0.61	0.35
6	Rest of South America	0.09	0.71	0.20
7	Northern Africa	0.50	0.25	0.25
8	Western Africa	0.02	0.12	0.85
9	Eastern Africa	0.10	0.15	0.75
10	Rest of Southern Africa	0.05	0.27	0.67
11	OECD Europe	1	0	0
12	Eastern Europe	0.11	0.83	0.07
13	Turkey	0.11	0.43	0.47
14	Ukraine region	0.12	0.78	0.10
15	Asia	0.11	0.14	0.75
16	Russia	0.06	0.29	0.65
17	Middle East	0.62	0.15	0.22
18	India	0.45	0.17	0.38
19	Korea	0.39	0.60	0.01
20	China	0.42	0.54	0.04
21	Southeast Asia	0.36	0.55	0.09
22	Indonesia	0.24	0.50	0.26
23	Japan	0	1	0
24	Oceania	0	1	0

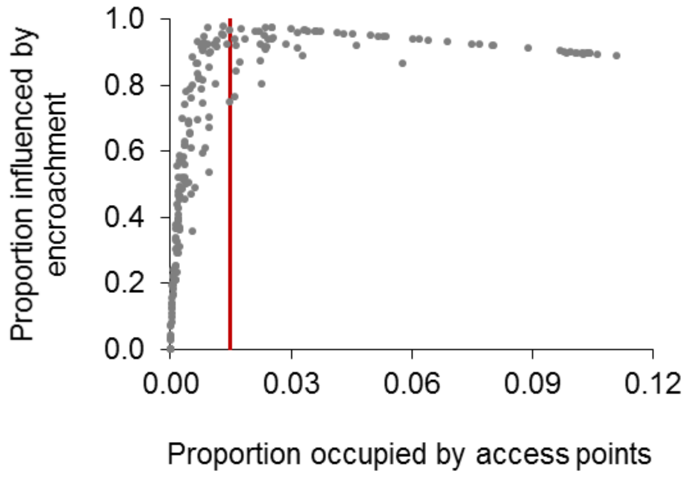
APPENDIX 3

Assessment of the encroachment threshold

The area influenced by human encroachment is dependent on the number and spatial configuration of human access points (for example, roads and settlements). The more human access points and the more dispersed within the landscape, the larger the total proportion of the landscape that is within the encroachment influence zone. In GLOBIO, it is assumed that human encroachment takes place in a 10 km zone around cropland and urban areas, which are considered proxies for human access points.

To test the influence of the amount and spatial configuration of these access points on the encroachment influence zone, a series of simulations was performed with a hypothetical landscape consisting of 50 x 50 cells. In each simulation, a certain proportion of these 250 cells was selected to represent human access points, according to a completely random or more clustered configuration. Then, the proportion of the 250 cells located within a distance of 10 cells (representing the encroachment impact zone of 10 km) from any access point was counted, to arrive at the relationship between the proportion of human access points and the proportion of a cell influenced by encroachment (Figure A3). Based on visual inspection, a value of 1.5% was selected as threshold for the proportion of human access points resulting in 100% of the 50 x 50 cell raster to be influenced by encroachment.

Figure A3 Relationship between the proportion of a hypothetical landscape that is occupied by cropland and urban area (which provide human access points) and the corresponding proportion that is influenced by human encroachment. The landscape consists of a hypothetical 50 x 50 cell grid and the encroachment impact zone is assumed to cover a zone of 10 neighbouring cells from any access point. The red line shows the threshold of 1.5%.



APPENDIX 4

Identifying encroachment cell types 1, 2 and 3

In the encroachment module of GLOBIO, first the cells are selected that contain more than 1.5% cropland and urban area (Type 1 cells). This is done on a resolution of 0.5° by 0.5°. For the remaining cells (less than 1.5% cropland and urban area), the proportion of cropland and urban area is determined based on a 'moving average' window that includes each target cell as well as its neigbouring cells. This is done at a resolution of 0.25° by 0.25°. To account for the fact that cell area decreases with latitude, the number of neighbouring cells included in the search window increases towards higher latitudes. In the zone around the equator (between 30° N and 30° S), a search window of 3x3 cells is used (0.75° by 0.75°). In the temperate zones (between 30° and 60° N or S) and high-latitude zones (> 60° N or S), the search windows are 4x3 (1° by 0.75°) and 5x3 cells (1.25° by 0.75°), respectively. Thus, the search window includes an increasing number of cells in east-west direction, but the number of cells covered in north-south direction remains constant.

After the proportions of cropland and urban area ($P_{crop,urban}$) have been determined for each moving average window, the proportions are assigned to the corresponding 0.5° by 0.5° cells. Then, each cell is assigned to type 1, 2 or 3, depending on the value of $P_{crop,urban}$ and whether the cell itself contains cropland or urban area or not, as follows:

- cells with more than 1.5% of cropland or urban area (type 1);
- cells with a proportion of cropland or urban area between 0 and 1.5% (type 2); and
- cells without cropland or urban area, yet located within 10 km of cells that do contain cropland or urban area (type 3).

Addendum I | GLOBIO version 3.6

In August 2016, the following corrections and adjustments have been implemented, resulting in GLOBIO version 3.6:

1) Cause-effect relationships for climate change have been adjusted such that for data-deficient biomes, the overall relationship is used rather than a relationship for a single other biome (see adjusted Table 3.1). In addition, the delay factor of 2 (see section 3.3) has been removed.

Table 3.1 Cause-effect relationships expressing the loss in MSA (1-MSA_{CC}) in relation to global mean temperature increase in °C (Arets *et al.*, 2014).

Biome	$MSA_{loss} \cdot {}^{o}C^{-1}$	SE	*p*-level	N
Boreal forest	0.0367	0.0125	0.005	48
Cool coniferous forest	0.1127	0.007	<0.001	15
Grassland and steppe	0.1201	0.023	<0.001	22
Hot desert	0.0521 [a]	-	-	-
Ice	0.0356	0.004	<0.001	8
Mediterranean shrub	0.0521 [a]	-	-	-
Savanna	0.0775	0.0104	<0.001	12
Scrubland	0.0661	0.0072	<0.0001	28
Temperate deciduous forest	0.071	0.008	<0.001	18
Temperate mixed forest	0.0487	0.0066	<0.001	18
Tropical forest	0.0521 [a]	-	-	-
Tropical woodland	0.1075	0.0128	<0.0001	39
Tundra	0.0426	0.0045	<0.001	8
Warm mixed forest	0.1457	0.0122	<0.0001	17
Wooded tundra	0.0521 [a]	-	-	-
Overall	0.0521	0.0047	<0.0001	239

[a] set equal to the overall MSA loss factor.

2) Cause-effect relationships for nitrogen deposition have been adjusted such that impacts are now included for plants and invertebrates only (i.e., no impacts on vertebrates, so the calculated impact counts for only 1/3 of the total impact). See adjusted Table 4.1.

Table 4.1 Cause-effect relationships describing the MSA due to nitrogen deposition in excess of the critical load (i.e., N_E in $g \cdot m^{-2} \cdot yr^{-1}$; see Eq. 4.1). Relationships were derived from Bobbink *et al.* (2010) and were then adjusted to account for impacts on plants and invertebrates only (i.e., 1/3 of the total impact).

Cause-effect relationship [a]		R^2	*p*-level	N	GLC2000 classes
original	$MSA_N = 1 - 0.220 \ln (N_E + 1)$	0.81	< 0.01	9	Forests (1- 10)
adjusted	$MSA_N = 1 - 0.0733 \ln (N_E + 1)$				
original	$MSA_N = 1 - 0.189 \ln (N_E + 1)$	0.96	< 0.01	12	Grasslands (11- 15)
adjusted	$MSA_N = 1 - 0.0630 \ln (N_E + 1)$				
original	$MSA_N = 1 - 0.145 \ln (N_E + 1)$	0.85	< 0.01	21	Snow and ice (20)
adjusted	$MSA_N = 1 - 0.0483 \ln (N_E + 1)$				

[a] Previously published in Alkemade *et al.* (2009).

3) The MSA for infrastructure disturbance is no longer differentiated between protected and non-protected areas (i.e., MSA_I = 0.78 everywhere).

4) The road impact allocation order has been adjusted to improve consistency: now, impacts are first allocated to the anthropogenic land-use classes (urban areas and croplands) and then to the (semi-)natural land-use classes (first outside and then inside protected areas). See adjusted Table 5.3.

Table 5.3 Priorities for assigning infrastructure impacted areas to GLC2000 land-cover classes within the GLOBIO model. PA = protected area; NA = not applicable.

Land-use class		Infra-priority		Natural habitat?
ID	**Description**	**No PA**	**PA**	
22	Artificial surfaces and associated areas	1	3	NO
16	Cultivated and managed areas (=cropland)	2	4	NO
30	Pasture	5	NA [a]	YES
10	Tree Cover, burnt	6	25	YES
19	Bare Areas	7	26	YES
18	Mosaic: Cropland / Other natural vegetation [b]	8	27	YES
13	Herbaceous Cover, closed-open	9	28	YES
12	Shrub Cover, closed-open, deciduous	10	29	YES
11	Shrub Cover, closed-open, evergreen	11	30	YES
14	Sparse Herbaceous or sparse shrub cover	12	31	YES
15	Regularly flooded shrub and/or herbaceous cover	13	32	YES
9	Mosaic: Tree cover / Other natural vegetation	14	33	YES
3	Tree Cover, broadleaved, deciduous, open	15	34	YES
17	Mosaic: Cropland / Tree Cover [b]	16	35	YES
2	Tree Cover, broadleaved, deciduous, closed	17	36	YES
8	Tree Cover, regularly flooded, saline, (daily variation)	18	37	YES
7	Tree Cover, regularly flooded, fresh	19	38	YES
6	Tree Cover, mixed leaf type	20	39	YES
5	Tree Cover, needle-leaved, deciduous	21	40	YES
4	Tree Cover, needle-leaved, evergreen	22	41	YES
1	Tree Cover, broadleaved, evergreen	23	42	YES
21	Snow and Ice (natural & artificial)	24	43	YES
20	Water Bodies (natural & artificial)	99	99	YES
23	Unknown	99	99	YES

[a] Pasture is never allocated to protected area; [b] Considered natural land cover because the cropland part has been 'removed' in the land-use module (see section 2.1.1, Eqs. 2.1 and 2.2).