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Deliverable 7.3

Deliverable 7.3: Report on detailed land use change at the national and regional level, including an assessment of economic, social, political and institutional drivers of change
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Abstract

Changes in land cover and other land processes can be caused by land use and by natural dynamics. In this report we present a newly constructed, spatially explicit database for the Human Appropriation of Net Primary Production for the period 2000-2013 that is aimed to complement the long time series (1900-2010) presented in D7.2. In a deomcomposition analysis, we scrutinize the individual weight of drivers of ecosystem processes such as net primary production (NPP), i.e. the role of natural changes, climate-induced, and land-use induced changes. Land-use change as environmental driver was further separated in land-use and land-cover conversion on one hand and land management on the other. While land-cover conversion is long known to represent a key environmental driver, land-management changes are much less studied. We here separate the land-management effect into land-use output intensity (the amount of biomass harvested per unit area) and land-use efficiency (the amount of NPP changed for each unit of harvest). This approach reveals that for many changes in the land system, changes in climate are dominant, with the noteworthy exception of land-use intensity effects in Europe and area-change effects in some regions in Africa. In the BACI transect, spanning from northern Europe to southern Africa, we found natural changes, area changes and management changes to be of similar importance on cropland. Climatic changes dominate the change within grazing lands and forests. However, some regions show hotspots of harvest intensity change, mainly increases in the last decade, albeit much more confined then climate-driven changes. Output intensity changes, i.e. harvest per unit area, are the most important driver of changes of human appropriation of NPP, while area changes play a minor role. For the later, regions in Africa represent noteworthy exceptions. Grazing and forestry dynamics dominate HANPP changes, while cropland dynamics, despite their large per-unit area impacts, play a subordinate role. The country level analyses for Ethiopia, Ukraine, Togo, and the Republic of South Africa confirm the pivotal role of climate drivers, but also disclose strong climate fluctuations without clear trends. This climate variability is difficult to interpret, because it often cancels out over periods, and it renders land-use change analyses difficult. Institutional changes, such as the collapse of the Soviet Union for the Ukraine with subsequent abandonment and later recovery, the end of dictatorship in Togo or Apartheid in South Africa, are reflected in the changes of land use, often not by simple changes in flows, but in variables such as the efficiency of HANPP use (ratio of harvest to HANPP). The dataset published and analysed here will allow for in-depth analysis of the BAC-Index and its underlying data streams by adding the socioeconomic, land-use dimension to this analysis.

1. Introduction

The socio-economic dimension of Biosphere-Atmosphere changes

Today, land use occurs on more than three quarters of the earth's terrestrial ecosystems (Ellis et al., 2013; K.-H. Erb et al., 2007; Luyssaert et al., 2014), providing food, energy and shelter to the world population, and at the same time resulting in severe sustainability challenges, such as degradation ,biodiversity loss or carbon emissions. At the same time, land use provides powerful means of climate change mitigation, .e.g by providing strong sinks for atmospheric carbon in reservoirs such as biomass or soil carbon pools (P. Smith et al., 2014).

Land use results in land cover conversions (i.e. the change from one land-cover type to another, e.g forest to grazing land) as well as land-cover modification, i.e. changes that occur within the same land-cover type (e.g. intensification of harvest in a forest). These two processes are key drivers of environmental change, resulting in the loss of carbon pools, eutrophication, air pollution, greenhouse gas emissions, topsoil loss, or biodiversity loss (Foley et al., 2005; IAASTD, 2009; Lindenmayer, Cunningham, & Young, 2012; Matson & Vitousek, 2006). With a growing world population, and ongoing changes in lifestyles, that affect diets, land is increasingly becoming a scarce resource which results in land-use competition and trade-offs that narrow the future options spaces (K.-H. Erb, Lauk, et al., 2016). An advanced understanding of dynamics of land-use as wells as its impacts is key for forging is key for forging strategies that allow to increase land-based production while avoiding or even reducing environmental detriments (Garnett et al., 2013; Lambin & Meyfroidt, 2011; Tilman, Balzer, Hill, & Befort, 2011; Verburg, Mertz, Erb, Haberl, & Wu, 2013).

However, many knowledge gaps relate to the impacts of land use on global change processes (K.-H. Erb et al., 2013; Kuemmerle et al., 2013; Steffen et al., 2015). A very basic and fundamental research challenge is that both, socio-economic drivers, i.e. land use, as well as climatic drivers influence climatic and ecosystem changes at various scales and it is difficult to disentangle the effects of both. This report approaches this major challenge, based on innovative methodological approaches and analytical tools that allow to distinguish socio-economic from climatic drivers of biosphere-atmosphere changes as well as the separation of land-cover conversions from land-cover modification effects.

Deliverable 7.3: Rationale and research objectives

WP7 of the BACI project focuses on the socio-economic dimension of biosphere-atmosphere changes. Deliverable 7.3 aims to establish national-level and regional accounts on changes in the land system in a decadal perspective for target countries and regions, and high-resolution maps of land use change. In D7.2 the focus was laid on the analysis of historic land use change, capturing the trajectory of land cover conversions and intensity changes in decadal steps from 1910 onwards. Comprehensive data on land-use (change) was collected, including information on land use changes and changes in land-use intensity (input and output) in a spatially explicit manner. However, in a historic, long-term perspective, data limitations are severe and do not allow for high temporal resolution; therefore, the time-steps addressed were only decadal time steps. This proved less suitable for the BACI project, but was at the time being unavoidable due to data availability. Recently, however, annual data on land-use as well as on land-cover became available that allowed for a higher temporal resolution after the year 2000 (in particular the HYDE database on land use as well as the ESA land-cover product (Klein Goldewijk, Beusen, Doelman, & Stehfest, 2017; Li et al., 2018). Building upon the methods developed for the long-tern, historic land-use study (WP7.2), the land-use database was prolonged at annual time steps for the period between 2000 and 2013. This, however, due to the use of recent maps, resulted in a slight incomparability between the two time series, the long one for 1910 to 2005, that was prolonged to 2010, and the short one for 2000-2013. This, incommensurability, however, relates only to spatially explicit results, because the new data availability affected only the basic down-scaling approaches ; the country-level data are still consistent and comparable. In this report, only results between 1960 and 2013 are displayed for the sake of simplicity.

As an analytical framework, in line with D7.2, we followed the "Human Appropriation of Net Primary Production" (HANPP)-framework that has gained momentum as a tool to assess the human domination of terrestrial ecosystems caused by land use. We use a decomposition approach to disentangle biophysical/climate-related and human-induced changes in NPP flows, which reflect political, economic and social drivers of land system change in the selected regions.

HANPP as an analytical framework

The ''human appropriation of net primary production'' or HANPP (H. Haberl et al., 2007; Vitousek, Mooney, Lubchenco, & Melillo, 1997) represents an indicator for anthropogenic land-use intensity and provides a framework for analysing the pressure exerted on terrestrial ecosystems by land use (Helmut Haberl, Erb, & Krausmann, 2014). It builds upon assessments of the human interference with net primary production. Net primary production (NPP) is the annual production of biomass by primary producers (mainly plants) available for heterotrophic processes in ecosystems. HANPP measures the effects of land conversions and biomass harvest on NPP and, by integrating metrics of output intensity and system-level changes (in this case, changes in NPP_{pot}), allows us to disentangle effects of changes in land cover and land-use intensity on ecosystem energetics (K. H. Erb et al., 2009; K.-H. Erb et al., 2013; Kuemmerle et al., 2013).

HANPP allows isolating the effects of climatic changes from effects of land use in terms of terrestrial NPP flows. Following Haberl et al. 2007, we define HANPP as the sum of two processes: A) biomass harvest through agriculture, forestry and livestock grazing ($HANPP_{harv}$) and B) indirect NPP appropriation through land cover change, such as it is the case when i.e. a natural forest is replaced by cropland or artificial pasture land ($HANPP_{luc}$). Hence, HANPP can be expressed through the following formulas:

$$HANPP = HANPP_{harv} + HANPP_{luc} \quad \text{(Equation 1)}$$

where

$$HANPP_{luc} = NPP_{pot} – NPP_{act} \quad \text{(Equation 2)}$$

NPP_{pot} represents the natural NPP level, i.e. the NPP that would occur in the ecosystem without human land use and NPP_{act} represents actual NPP, i.e. the currently prevailing NPP as the combined NPP of all occurring land use classes (agriculture, forestry, infrastructure, livestock production).

Analysing NPP flows within the HANPP framework is an important contribution towards an understanding of the key drivers of land use change and enables us to disentangle natural from anthropogenic drivers and land cover change from land management change. This is accomplished by first describing land use change of the past 70 years on a global level, revealing temporal and spatially specific dominant land use transitions. Focusing then on the BACI transect over Europe and the African continent, changes in NPP and HANPP flows in the period 2000 to 2013 were analysed and decomposed to distinguish between the influence of natural dynamics and changes in land use. The latter was eventually separated into land cover changes and land management changes.

For selected countries, i.e. Ukraine, Togo, Ethiopia and South Africa, HANPP changes are then put into the country specific context of socioeconomic dynamics of the recent past.

2. Materials and methods

In WP7.2 HANPP trajectories were calculated in a decadal time series from 1910 to 2010 on a global level at 5 minute resolution. We now extended this calculation annually for 2000 to 2013, for a better fit with the BACI time series (relevant for WP7.4 and its deliverable).

In analogy to the long-term reconstruction of HANPP 1910-2010, we combined the best available, spatially explicit land cover/-use data sets with census data on biomass harvest, as well as with model outputs for NPP_{pot} , also for the assessment of the annual HANPP between 2000 and 2013. We follow a closed budget approach, i.e. considering 100% of each grid cell globally by quantifying land cover/-use trends of all occurring land-use types, such as cropland, forest land, grazing land and settlement areas. Unused and unproductive areas, such as permanent hot and cold deserts, are not assumed to have any effect on HANPP and are thus excluded from our calculation. The following subsections describe all data sets and methods used in more detail.

Land-use data set

Land-use data set for decadal time series from 1960 to 205

The method for the decadal time-series reconstruction is outlined in detail in D7.2. For the sake of completeness, the principle is presented here. This long time series reaches back to 1910, but the period of analyses is chosen to be from 1960 onwards.

For the decadal time steps from 1960 to 2010, the land use data set follows the approach outlined in D 7.2. In general we established layers for the different land use types outlined in this section and then reduce areas of the land-use with lower priority in case the total area in a cell would be larger than the available total land area in that cell (closed-budget approach, see (K.-H. Erb et al., 2007). The land-area mask was taken from the HYDE 3.2.1 data. For built-up and cropland area we used HYDE 3.2.1 data as basis (cropland data in Hyde matches FAOSTAT data for this period). However, as built-up data in HYDE does not consider rural infrastructure areas, we considered that each cropland pixel contains a certain amount of rural infrastructure (3% of cropland area in 1910 linearly increasing to 5% in 2010). For non-productive area we used data on bare lands from the ESA land cover dataset (https://www.esa-landcover-cci.org/; (Defourny, 2017)) for the year 2000 and kept it constant throughout time as information on the long term evolution of these areas is lacking. For grazing areas, we used pasture and rangeland layers of the current HYDE data base..

Wilderness areas (i.e. areas without land use) were also taken from the Hyde 3.2 dataset which also provides an “re-classification of HYDE 3.2.000 according to the Ellis and Ramankutty (2008) scheme of “Anthropogenic Biomes” or “Anthromes”. The remaining areas were defined either as *forests and woodlands* or *other land may be grazed*. Forests and woodlands were considered in those pixels that were classified as potential forests in two of three maps of potential vegetation (FAO, 2001; Olson et al., 2001; Ramankutty & Foley, 1999). All other pixels are considered “other land may be grazed”. Additionally, on pixels classified as village land in the HYDE “Anthromes” data (Ellis & Ramankutty, 2008) 90% of the hitherto unclassified land were defined as other land may be grazed, while 10% were considered forest land. This approach was chosen in order to account for the proximity of more intensively used land classes, such as pasture land, to villages and infrastructure areas.

Land-use data set for annual time series from 2000 to 2013

For the short annual time series from 2000 to 2013, the calculation of cropland and built-up areas followed a similar methodology as for the time series from 1910 to 2010. Differences in the approach relate to details and databases to calculate forest land, grazing land and wilderness. Benefiting from the ESA CCI-LC project, which provides the public with annual global land-cover maps from 1992 to 2015 using a typology of 38 land cover classes at a resolution of 300m (Defourny, 2017), a new global forest layer was created. We rescaled the provided layers to a 5 minute resolution and summarized ESA land cover categories to produce maps of closed forest areas (CCI-LC categories 50, 60, 61, 70, 71, 80, 81, 90, 160 and 170, which comprises all areas with a tree cover greater than 40%) and open forest areas (CCI-LC categories 62, 72, 82, 100 and 110, which comprises all areas with a tree cover between 15% to 40%).

Wilderness was calculated by combining human footprint data (Venter et al., 2016b, 2016a), i.e. a spatially explicit inventory of human artifact density, and intact forest landscape data (Potapov et al., 2017). Intact forest landscape data only pertains to a forest zone (as defined by Potapov), while human footprint data is available globally. Since human footprint data is only available for 1993 and 2009 and intact forest landscape data only pertains to 2000 and 2013 annual values from 2000 to 2013 were calculated by linear interpolation. We defined wilderness as areas with the value 0 on a 0 to 50 scale of the human footprint and areas covered with an intact forest landscape. The combination of the two dataset resulted in a definition of core wilderness areas on forested land (both datasets indicate wilderness), and periphery wilderness (in cases when only one dataset identified the area as wilderness), both in fraction-per-gridcell representation.

The layer on forest cover was used to allocate the area that was not allocated to cropland (HYDE 3.2.1), infrastrucutre land (following the pincple described above), permanent pasture (from HYDE 3.2.1), and wilderness to forest (within the forest mask) and “other land may be grazed” (outside the forest mask). In order to account for free-range grazing livestock, 25% of peripheral wilderness areas was assumed to be grazed. Similarly, anther 25% of peripheral wilderness was assumed to be under wood fuel collection schemes. Core wilderness areas were assujmed to be unmanaged.

Calculation of land use transitions

The gridded land-use datasets allowed to calculated gross and net land-use change (see eg. (Li et al., 2018; Richter & Houghton, 2011). Transitions between the major land use types cropland, grazing land and forest land were calculated from 1960 onwards. By identifying the signed absolute difference for each land use type per grid cell and finding the two greatest differences with opposite signs, the main land use transition per grid cell was determined, with its extent being the smaller value of the two involved land use types. All other secondary land use transitions within a cell were summarized into the category “other” (see figure 1).

Calculation of Biomass flows (HANPP components)

$HANPP_{harv}$: Biomass harvest

Biomass harvest on croplands, forest land and grazing land were calculated following the calculation steps outlined in Krausmann et al. (2013). For 1960, 1970, 1980, 1990, 2000 and 2010 (“long time series”), 3-year averages were computed. For the time period 2000-2013 annual data were used. The FAOSTAT database was the central underlying data source (date of data access: September 3, 2018). Data were calculated at the national level for the country classification available for the given year in FAOSTAT (e.g. for the USSR before 1991 and for its succession countries thereafter).

The treatment of permanent crops was slightly different in our calculations compared to Krausmann 2011. In order to take into account that NPP on permanent cropland is not necessarily linked to harvest volumes, we assumed that additional to reported primary crop harvest, areas of permanent crops exhibit half of as NPPpot as NPPact, and half of this additional NPPact is counted as HANPPharv.

Cropland harvest was spatially downscaled to the HYDE 3.2.1 cropland patterns following an index created through the combination of NPP_{pot} patterns, cropland extent patterns, the extent of irrigated land (HYDE 3.2. based on Siebert et al., 2015), as well as data on the spatial evolution nitrogen fertilizer application (Zhang et al., 2017). We assumed that cropland yields were higher in regions of high NPP_{pot}, where temperature and water availability are usually favourable for agricultural production, as well as on irrigated land and on land with high fertilizer input, where aridity and / or nutrient limitations are counterbalanced through external water inputs (Niedertscheider et al., 2016; W. K. Smith, Cleveland, Reed, & Running, 2014).

No data on spatially explicit forest harvest exists, which is why we assumed forestry harvest to follow the patterns of forest NPP_{pot}. However, we excluded areas that were defined as “wilderness” (see above). Harvest on grazing land was calculated based on calculating feed demand (through livestock numbers and feed requirements) and subtracting available feed stuffs from the overall demand. Krausmann et al. 2013 outline the general principle. As FAOSTAT has stopped reporting (and removed previously existing) production and area of cropland used for dedicated fodder crops (e.g. green maize), we slightly deviated from Krausmann et al. here, in that we also allocate livestock grazing partly on fallow land. Fallow land is calculated as the difference between cropland area reported in FAOSTAT (which includes lands planted to crops and lands fallowed for a maximum of 5 years) and the harvested crop area reported in FAOSTAT.

Harvest on grazing land was downscaled to the grid following the HYDE 3.2.1 patterns of grazing land. Two basic considerations were important here:

1. The fraction of NPP_{act} on grazing land that is available for grazers had to be defined. On grazing land pixels that belong to pasture land in HYDE 3.2.1, the entire aboveground fraction (50% of total NPP; Haberl et al. 2007) was considered accessible for grazers, while on rangeland and other land may be grazed a certain fraction was assumed to be covered by woody vegetation and thus was excluded from grazing, i.e. in the case of savannahs, or shrublands. Here, we used values provided by Fetzel et al. (2017), who provide the following factors:

- natural grasslands: 100% of aboveground NPP
- other wooded land: 70% of aboveground NPP

These factors were spatially joined with three different biome maps (FAO, 2001; Olson et al., 2001; Ramankutty & Foley, 1999), where the mean factor between the maps was taken as a multiplier for NPP_{act} in each pixel.

2. For the allocation of grazed biomass into the grid, we additionally followed a grazing-intensity function assuming that regions of high NPP_{act} are over-proportionally grazed compared to regions of lower NPP_{act}.

Table 1 summarizes the allocation schemes for harvest flows to the individual land-use layers for the long time series and for the short time series.

Table 1. Allocation scheme of harvest flows (HANPPharv) to the individula land-use layers.

Assigned HANPPharv / Land use (in order of authority)↓	Long time series: crop harvest	Long time series: grazing	Long time series: wood harvest	Short time series: crop harvest	Short time series: grazing	Short time series: wood harvest
Built up						
Cropland	*	*		*		
Non-productive / snow						
Wilderness (core)						
Wilderness (periphery)					*	*
**Woodland			*			
**Closed forest						*
**Open forest					*	*
Grazing land		*			*	
Other land, may be grazed		*			*	

** Woodland available in the long, closed and open forests in the short time series

Actual NPP (NPP_{act})

Actual cropland NPP was extrapolated from cropland $HANPP_{harv}$ using country-specific pre-harvest loss factors. These factors were taken from Krausmann et al. (2013) and are account for the decrease of NPP losses in the course of industrialization of land-use (Gingrich et al., 2015a). In line with common practice in HANPP studies, NPP_{act} on forest land was assumed to equal NPP_{pot} (K.-H. Erb, Fetzel, et al., 2016; Noormets et al., 2015) and NPP_{act} on infrastructure land was considered to be one third of NPP_{pot} assuming one third of the area carries highly productive vegetation (Helmut Haberl et al., 2014). On grazing land located on potential forest land 20% of NPP_{pot} were deducted to arrive at NPP_{act}. Additionally, to account for degradation on grazing land, deduction factors derived from Zika and Erb (2009) were applied. In the present version, the low estimate was used to arrive at conservative results.

Potential NPP (NPP_{pot}) and HANPP

Potential NPP (NPP_{pot}) trends were calculated by the LPJguess model (B. Smith et al., 2014). Several LPJ-runs exist, where we use the version closest to Krausmann et al (2013) in order to warrant the highest possible level of consistency. HANPP was finally calculated as the sum of $HANPP_{harv}$ and $HANPP_{luc}$ (defined as the difference between NPP_{pot} and NPP_{act}).

Identifying and quantifying drivers of change: Decomposition analysis

As an analytical tool to identify drivers of change a decomposition analysis was performed for various crucial target variables. Decomposing the absolute change between two points in time of the variable of interest into the contributions of the factors of the developed identity enables us to conclude which changing factor has how much impact on the trajectory of the variable. For all introduced identities the analysis followed (Chung & Rhee, 2001) method of "mean rate-of-change index" decomposition.

To attribute the change of actual NPP (NPPact) to climatic versus human induced drivers, following identity was developed:

$$NPP_{act}\left[\frac{tC}{yr}\right] = Area[km^2] * \frac{NPP_{pot}\left[\frac{tC}{yr}\right]}{Area\,[km^2]} * \frac{NPP_{act}\left[\frac{tC}{yr}\right]}{NPP_{pot}\left[\frac{tC}{yr}\right]} \qquad \textit{(Equation 3)}$$

Interpretations of the factors: Biophysical changes in the environment are represented by the second factor $\mathrm{NPP_{pot}}\left[\frac{\mathrm{gC}}{\mathrm{m}^2}/\mathrm{yr}\right]$, human induced land cover changes by the first and changes in land use management by the third which is a different expression of the aforementioned HANPP component HANPPluc. For methodological reasons in the calculation of HANPP, HANPPluc is Nil by definition on forest land and never changes on built-up areas. For grazing land HANPPluc only changes when expansion onto potential forest land or into degraded areas occurs.

To depict the impact of changes in land use management on all land use types an identity for the decomposition of remaining NPP after harvest (NPPeco) was created.

$$NPP_{eco}\left[\frac{tC}{yr}\right] = Area[km^2] * \frac{NPP_{pot}\left[\frac{tC}{yr}\right]}{Area\,[km^2]} * \frac{NPP_{act}\left[\frac{tC}{yr}\right]}{NPP_{pot}\left[\frac{tC}{yr}\right]} * \frac{NPP_{eco}\left[\frac{tC}{yr}\right]}{NPP_{act}\left[\frac{tC}{yr}\right]} \qquad \textit{(Equation 4)}$$

By decomposing NPPeco we can add the factor $\frac{NPP_{eco}\left[\frac{tC}{yr}\right]}{NPP_{act}\left[\frac{tC}{yr}\right]}$, which represents the HANPP component HANPPharv and depicts the output intensity of land use systems. Harvest on built-up land is by definition never changing, therefore we excluded this land use type from being depicted in the results section.

Additional to separating climatic and human induced drivers of change, we also performed a decomposition analysis of HANPP itself, using an identity introduced by Gingrich et al. (2015). This decompostion allows to scrutinize different land-use effects, i.e. the differentiation between intensity (second factor) and efficiency (third factor) changes.

$$HANPP\ [\%] = Area\ [km^2] * \frac{HANPP_{harv}\left[\frac{tC}{yr}\right]}{Area\ [km^2]} * \frac{HANPP\ [\%]}{HANPP_{harv}\left[\frac{tC}{yr}\right]} \qquad \text{(Equation 5)}$$

The intensity factor captures changes in output intensity defined as harvest per unit area. Efficiency as used here describes how much HANPP is induced by land use for each unit of $HANPP_{harv}$.

Taking into consideration that HANPPluc is always Nil on forest land (see above) the third factor of equation 5 has to be rearranged for forest land:

$$\frac{HANPP\ [\%]}{HANPP_{harv}\left[\frac{tC}{yr}\right]} = \frac{\frac{HANPP_{harv}\left[\frac{tC}{yr}\right]}{NPP_{pot}\left[\frac{tC}{yr}\right]}}{HANPP_{harv}\left[\frac{tC}{yr}\right]} = \frac{1}{NPP_{pot}\left[\frac{tC}{yr}\right]} \qquad \text{(Equation 6)}$$

It therefore expresses climatic changes in NPPpot (productivity) rather than efficiency changes.

The factors HANPPluc, HANPPharv (equations 3 and 4), efficiency (equation 5) and productivity (equation 6) all produce an inverse signal to the decomposed variable, meaning that an increase in HANPPluc, HANPPharv, efficiency or productivity decreases NPPact, NPPeco and HANPP respectively.

Mean rate-of-change index decomposition and analytical depiction

The contributions of the individual factors to the change of the target variable (NPPact, NPPeco, HANPP) between two point in time are calculated as follows:

$$\Delta variable = \Delta factor1 + \Delta factor2 + \Delta factor3\ (+\Delta factor4)$$

$$\Delta factor_i = M * \frac{f_{i_2} - f_{i_1}}{\bar{f_i}}$$

$$M = \frac{variable_2 - variable_1}{X}$$

$$X = \frac{f_{i_2} - f_{i_1}}{\bar{f_i}} + \frac{f_{i+1_2} - f_{i+1_1}}{\bar{f}_{i+1}} + \cdots + \frac{f_{n_2} - f_{n_1}}{\bar{f_n}}$$

$$\bar{f}_i = \frac{f_{i_1} + f_{i_2}}{2} \qquad \text{(Equations7)}$$

$variable \ldots NPPact, NPPeco, HANPP \qquad i = [1, n]\ (with\ n = 3\ or\ n = 4)$

The decomposition analysis was performed on the three major land use types cropland, grazing land and forest land for each identity. The change of the target variable was attributed to one of the factors when their contribution was greater than 50% of the sum of the contributions of all factors (in absolute values).

For the identities NPPact and HANPP, not only one land use type but the combination of all land use types within a grid cell was analysed. This allows to to identify the major (land use type specific) driving force of change, but only with some ex-post adaptations: Area change, when analysing the whole cell, will mostly be Zero, except for changes concerning wilderness and unproductive and snow areas. Therefore, the area effect will be set to zero if not corrected. To take this into account, we summed the contributions to the change of the target variable from the area change of each land use type. This the represents the contribution to change from the conversion of land use types within a given area. It is important to note that area changes can not be attributed to individual land-use types (as always at minimum two land-use types are involved in any land-use change, and the individual weigths calculated by the decomposition analysis refer to relative contributions and are not summable).

NPPpot changes pose a similar problem, since in our basic modelling approach productivity increase or decrease are the same for all land use types within a grid cell. The magnitude of the contribution is defined by the area extent of the land use type, but since the NPPpot change affects the whole grid cell and not just a fraction of it, these contributions were added up as well to get a measure for the effect of productivity change on the target variable. HANPPluc, intensity and efficiency, in contrast, are indeed specific to a land use type and can thus be accounted for separately, even when analysing the whole grid cell with its mix of land use types.

For HANPP we analysed the land use combination within a grid cell in two different ways. First we decomposed the change of HANPP into area change as described above. The factors intensity and efficiency in this analyses were defined as the sum of the intensity change on cropland, grazing land, forest land and built-up land and the sum of efficiency change on cropland, grazing land and built-up land. Forest land was excluded as it does not have an efficiency measure as defined above. This analysis enables us to differentiate between area conversion, overall intensity change or overall efficiency change as the driving force behind the change of the target variable HANPP.

The second analysis was designed to attribute the change of HANPP to the change of land use management on a specific land use type. Thus we summarized the contribution of intensity and efficiency change per land use type, again using only the intensity measure for forest land. The combination of area changes was handled as described above.

As before attribution of the change of the target variable to a singular factor only occurred when the factor's contribution was greater than 50% of the sum of the contributions of all considered factors (in absolute values).

Auxiliary data for analysing socio-economic change

To include indicators for socio-economic change we added three variables. First we took population numbers provided by the United Nations (https://population.un.org/wpp/Download/Standard/Population/WPP2017_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx). Second, economic activities associated with land-use were described using numbers from the National Accounts Main Aggregates Database from the UN Stats (https://unstats.un.org/unsd/snaama/dnllist.asp). The International Standard Industrial Classification of All Economic Activities (ISIC) reports in the sections A and B GDP produced by agriculture, hunting, forestry and fishing. And third, the area equipped for irrigation as share of cropland using the Historical Irrigation Dataset (Siebert et al., 2015) as input.

3. Results & Discussion

Global patterns of land use change in the last decades

Land use transitions

In the decades since 1960[1] global land use is characterised by the expansion of cropland, which was at its height between 1980 and 1990 with a net increase of over 700 000 km² after already experiencing massive net increases from 1910 to 1960. Following patterns already described by (Ramankutty, Foley, & Olejniczak, 2002) we see a significant expansion of cropland on former grazing and forest land in southeast Brazil, Argentina, northeast China, Australia and southeast Asia. From 1960 to 1980. The expansion of cropland was accompanied by net loss of forest land and grazing land. Figure 1 and 2 show the development of land use transitions, displaying the major gross conversions to and from one type from and to another type.

Conversions between cropland and grazing land are the most common. Especially the recent past between 2000 and 2013 exhibits an obvious contrast between the Northern and Southern hemisphere, with conversions from cropland to grazing land being prominent in the US and parts of Europe, while grazing land is converted to cropland in Brazil, Argentina and Sub-Saharan Africa. Transitions between cropland and forest land are least prevalent and declining over the past 50 years, having had their peak between 1950 and 1960. A return of the forest on former cropland is observable in parts of North America between 1960 and 1990, but followed by a reconversion into cropland between 1990 and 2000. Europe's West experienced a conversion of cropland and grazing land into forest land between 1960 and 1990, notably in France from 1960 to 1980 (as described by (Mather, Fairbairn, & Needle, 1999)). After 1990 Ireland, Austria and south eastern Europe display large scale transitions from cropland and grazing land to forest land, being driven in the East by the abandonment of agriculture in the post-communist era and a transition to de-intensification and commercialization (Jepsen et al., 2015). Transitons of wilderness area peaked in the year 2007-2009, which is a reproduction of the input data presented in (Potapov et al., 2017; Venter et al., 2016b).

[1] Note that in this report we only refer to changes since 1960 to reduce complexity, and focus mainly on the annual results after the year 2000, which is the period of regard for BACI.

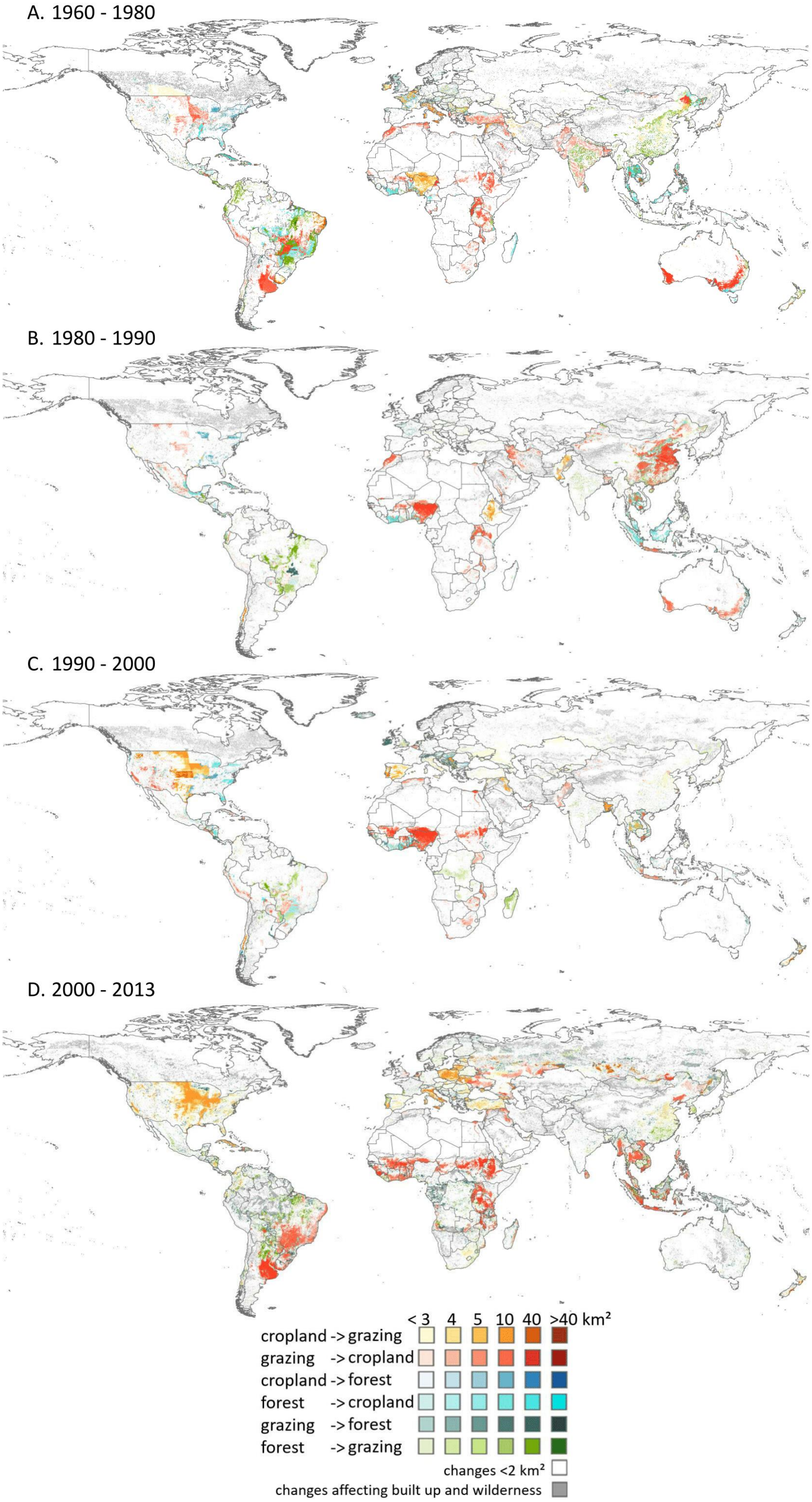

Figure 1: Global patterns of land use transitions for A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013. Transitions are colour coded for their extent within a 5x5min grid cell.

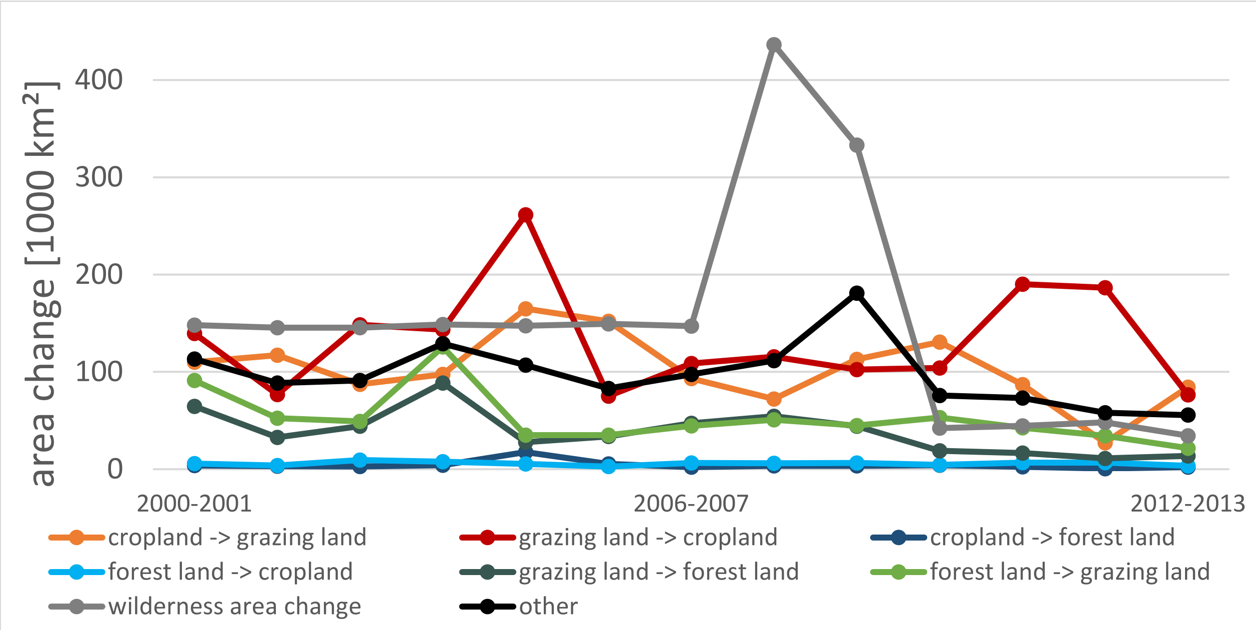

Figure 2: Globally summarized annual extents of land use transitions within the period 2000 to 2013.

HANPP

In the course of the 20th century global NPP appropriation measured by the HANPP indicator framework, has doubled (Krausmann et al. 2013). Following the calculation procedures outlined above results in a HANPP 10.5 billion (bio) tons carbon (tC) in 1960, which increased to 13.0 bio tC in 2000 and continued to rise to 14.6 bio tC in 2013. This HANPP result is slightly lower than the results in Krausmann et al. (2013), owing to the spatially explicit calculation of HANPP and its indicators that allows for the more fine-scale representation of land use impacts, taking into account also local to regional ecosystem properties, as well as changes in key input variables such as NPP_{pot}.

Expressed as a share of natural NPP (NPP_{pot}) the HANPP increased from 18.7% (in 1960) to 20.8% (in 2000) and 22.7% in 2013. Similar levels of annual average change can be observed between 1960 and 2013 (Figure 3). The collapse of the Soviet Union lead to a very pronounced HANPP decrease between 1990 and 2000, with a decline being already visible between 1980 and 1990. Since 2000 a recuperation to former HANPP levels in the countries of the former Soviet Union is visible. South America, especially the Amazon region experienced strong increases in HANPP since 1960, mainly between 1960 and 1980 and since 2000. Western Europe displays continuously decreasing HANPP % NPPpot, while Southern and Eastern Asia experienced mainly increasing HANPP between 1960 and 1990, but since then exhibit growing areas with decreasing HANPP.

Our findings resemble the archetypical HANPP patterns described in previous studies (Gingrich et al., 2015a; Jepsen et al., 2015; Kastner, 2009; Krausmann et al., 2012): HANPP starts at low levels and usually increases owing to population growth and resulting land expansion under relatively low biomass yields. In the course of industrialization followed by intensification of agriculture, HANPP stabilizes at high levels, as biomass demands are not satisfied by expanding agricultural areas, but by increasing outputs per area.

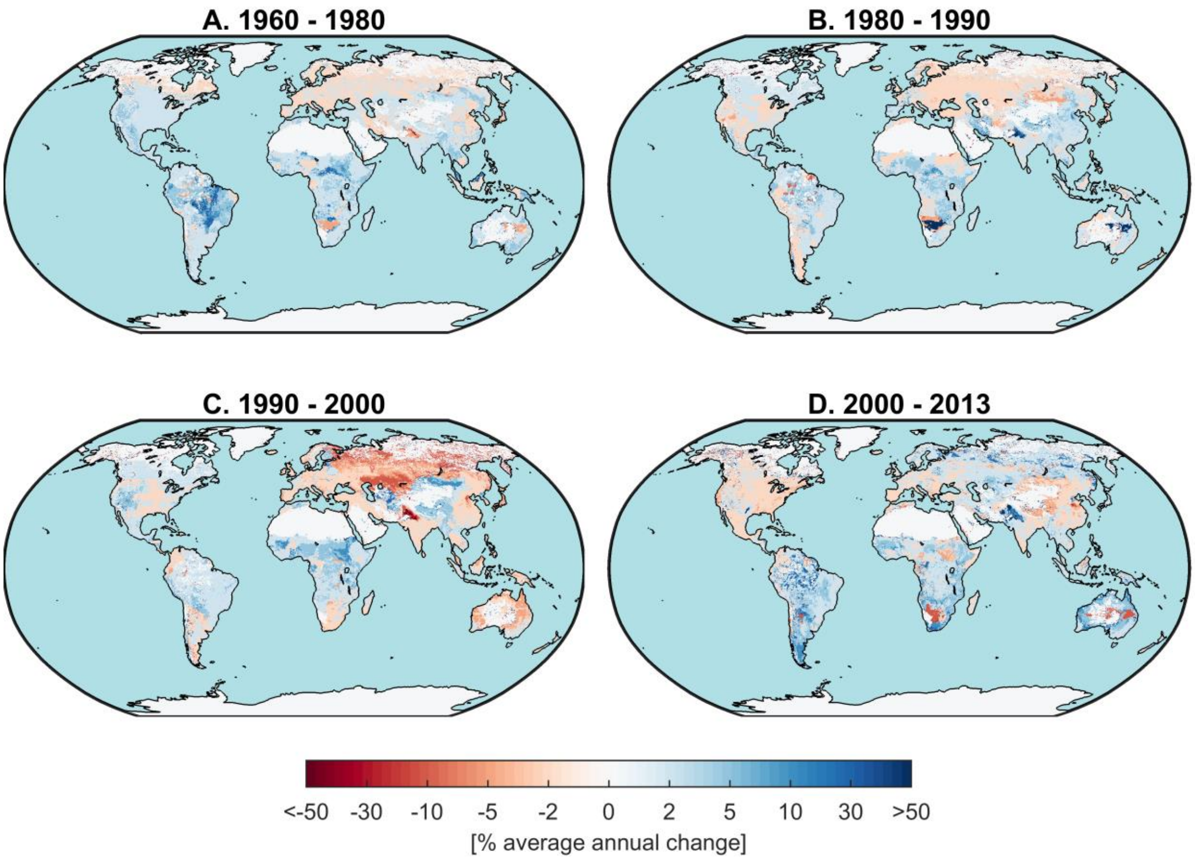

Figure 3: Annual average changes of HANPP [% of NPPpot] in percent absolute change from A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013.

NPPpot and NPPact

HANPP developments are intimately linked to potential NPP trajectories (Krausmann et al., 2013). NPPpot showed a global rise from 56.1 bio tC in 1960 to 62.9 bio tC in 2000 and 64.3 bio tC in 2013, owing to climatic changes, increasing N-availability and rising CO_2 levels in the atmosphere (Sitch et al., 2003). Figure 4 reveals the variability of NPP, showing regions with alternating trends of decrease and increase. Especially from 2000 to 2013 we see large annual average changes in NPP in the Subtropics (figure 4), which in some parts are contrary to the development in the decade prior. NPPpot changes are particularly pronounced after 1990.

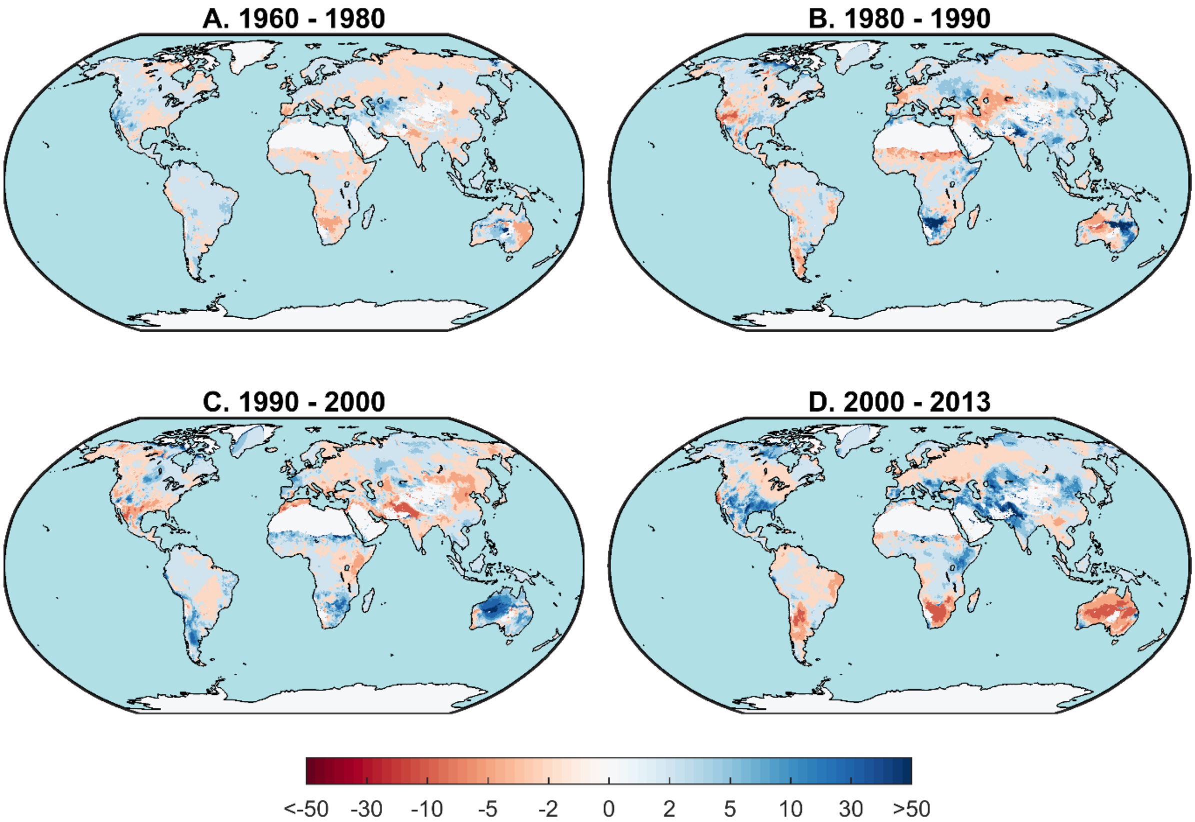

Figure 4: Annual average changes of NPPpot [gC/m²/yr] in percent absolute change from A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013. Same legned as Figure 5.

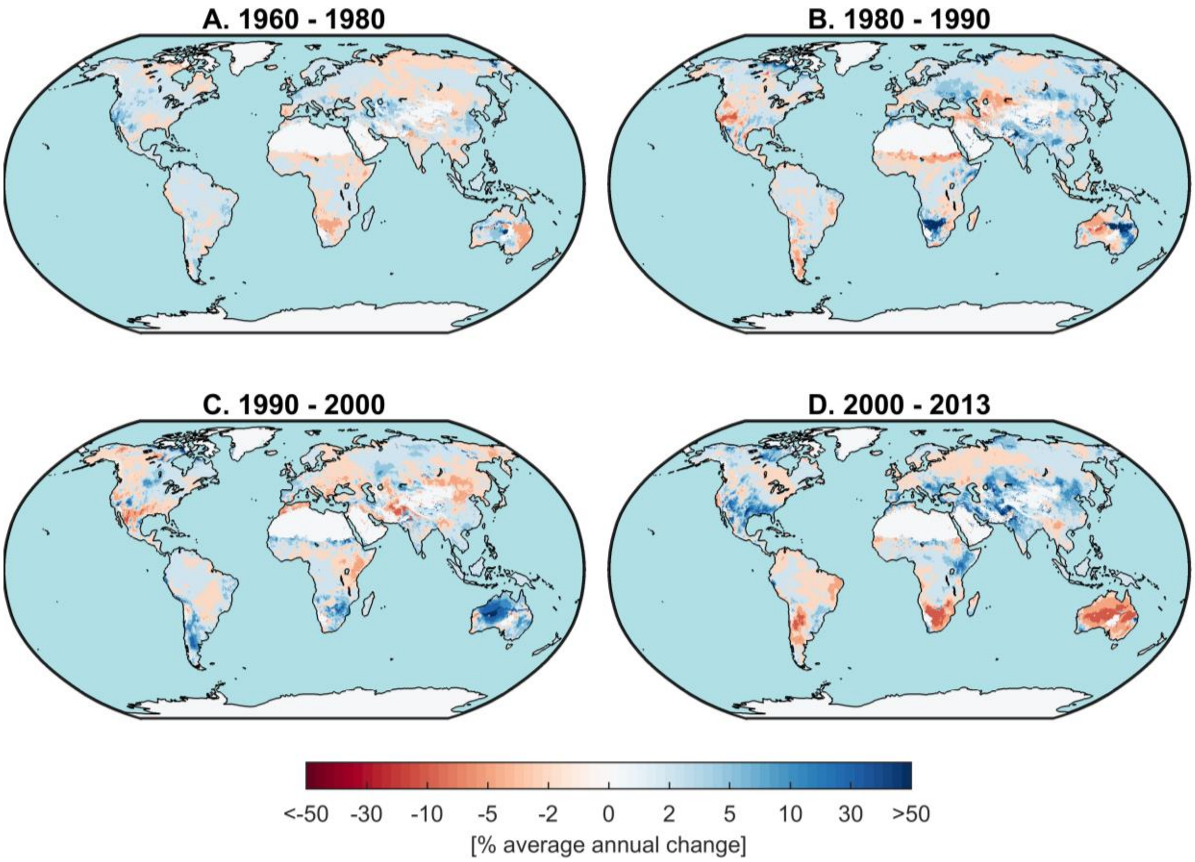

Figure 5: Annual average changes of NPPact [gC/m²/yr] in percent absolute change from A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013.

NPPact closely follows the development of NPPpot, but also shows exemptions where land use management decouples actual NPP production from the annual fluctuations of NPP. These changes are are particularly pronounced in Europe and North America, but also in southern Asia (Figure 5) and repesent HANPPluc (discussed below).

HANPPharv

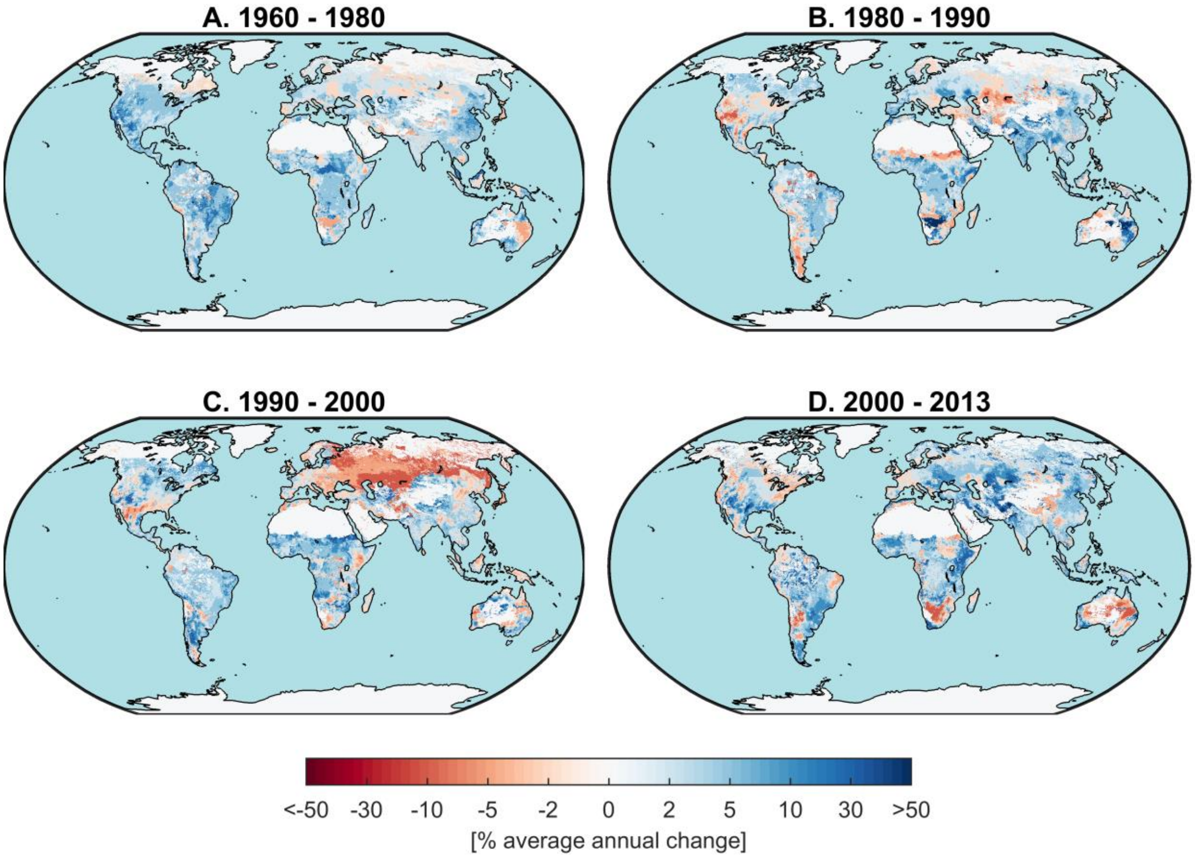

Figure 6: Annual average changes of HANPPharv [gC/m²/yr] in percent absolute change from A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013.

Harvest shows massive increases in all observed periods, increasing from 2.1 bio tC in 1960 to 8.1 bio tC in 2000 and 10.3 bio tC in 2013 (Figure 6). The collapse of the Soviet Union is the noteworthy exemption to this trajectory and a prime example for the impact of institutional changes on land use (Prishchepov, Radeloff, Baumann, Kuemmerle, & Müller, 2012; Schierhorn et al., 2013). From 2000 to 2013 we see a decrease in HANPPharv in parts of Europe and North America and a pronounced decline in Australia and south Africa, which could be induced by aforementioned NPPpot changes.

HANPPluc

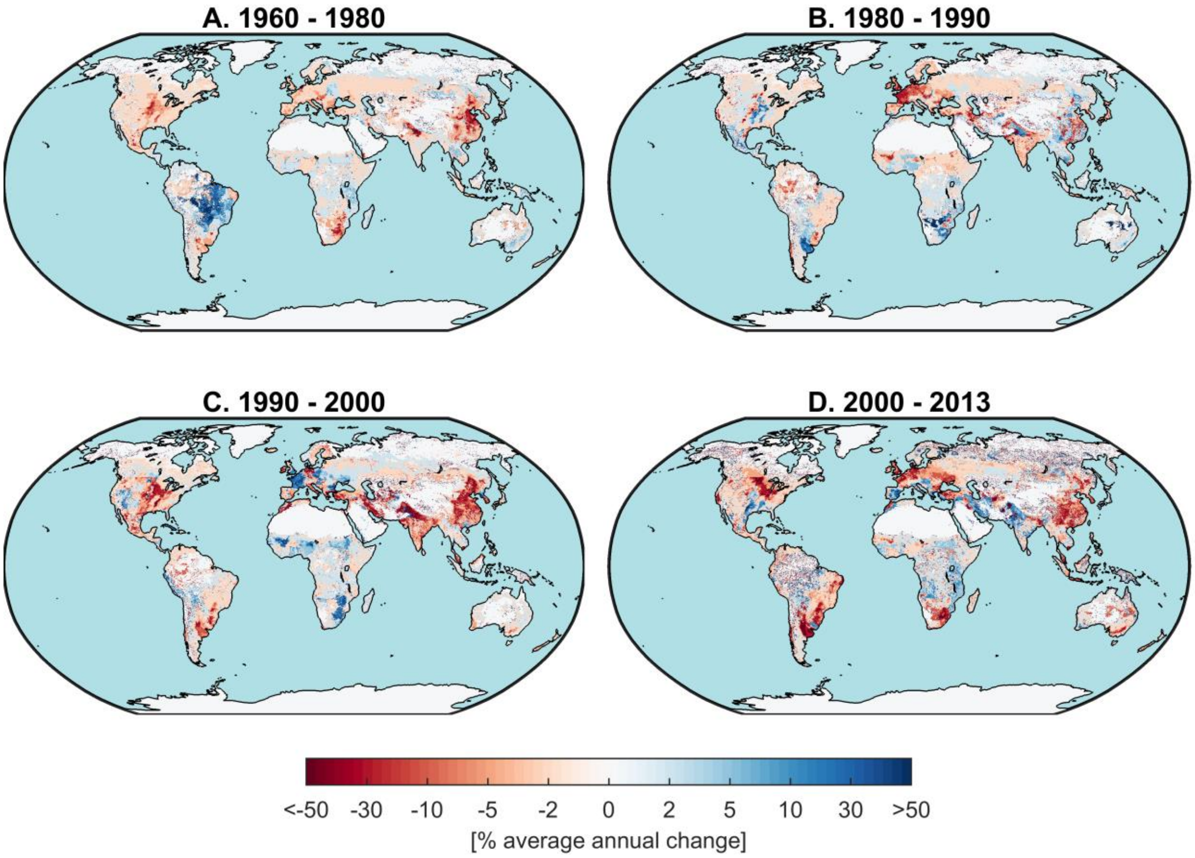

Figure 4: Annual average changes of HANPPluc [% of NPPpot] in percent absolute change from A.1960-1980, B. 1980-1990, C.1990-2000 and D. 2000-2013.

HANPPluc (figure 7), as the difference between NPPpot and NPPact (see above) represents the biomass lost or gained through land cover conversions. An increase in HANPPluc therefore is caused by a rising loss of NPP due to land cover conversion, a decrease on the other hand signifies that NPPact is closer to NPPpot (or even suprases NPPpot) than before. In many regions, HANPPluc decreases over all periods, notably in Central Europe and North America. The Amazonian region displays rising HANPPluc between 1960 and 1980, owing to increases of cropland productivity (at low levels). Note that certain transition dynamics, e.g. forest to grazing land, are not necessarily detected in HANPPluc, because for forest HANPPluc is assumed to be nil and a fixed percentage of NPPpot is applied for NPPact on grazing land. Notable from 2000 to 2013 is an increase of HANPPluc in Southern Europe, which in Italy could be caused by conversion from cropland to grazing land (as shown in figure 1).

Decomposition of biomass flows

The decomposition of biomass flows enables us to discern between climatic and human induced drivers of change, which then can be further investigated from according analytical viewpoints. Figure 8 displays the global pattern of NPPact for the tree periods analysed in the decomposition analysis. In the ensuing chapter, the decomposition will be displayed for the BACI transect, which spans from Northern Europe to Southern Africa.

NPPact

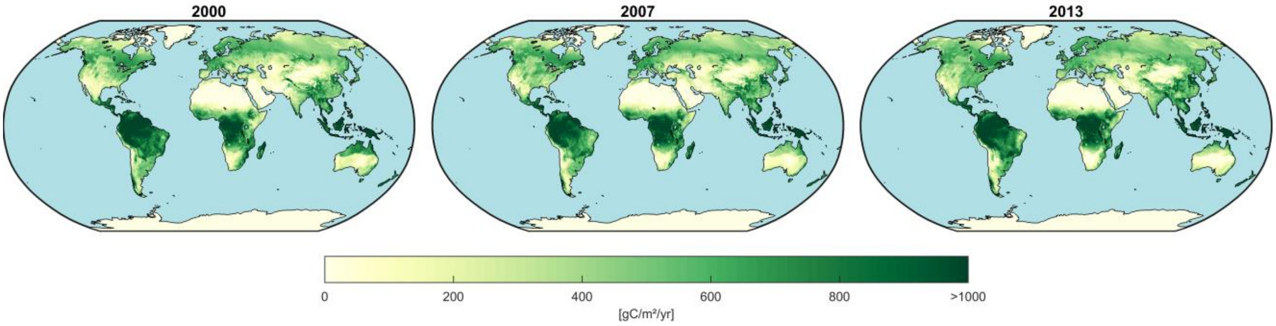

Figure 5: NPPact [gC/m²/yr] for 2000, 2007 and 2013.

Decomposition analysis of NPPact

Climatic changes expressed as NPPpot changes are the most common main driver of changes of NPPact for all analysed periods (Figure 9). Annual climate fluctuations seem to oscillate, creating an increase during one period, followed by a decrease in the next. Europe displays such a behaviour, with increasing NPPpot leading to a rise of NPPact between 2000 and 2007 in some parts, which then experience the opposite trajectory between 2007 and 2013. For the overall period 2000 to 2013 this leads do a mosaic of both trajectories.

Area conversions of land use types as the main driver of NPPact change are of considerable relevance for the period 2000 to 2007 (Figure 19), almost exclusively in the most Northern and most Southern latitudes. Changes in grazing land management rarely have a great impact on NPPact, but occasionally play a minor role in Northern Africa.

Only in Ukraine, Poland and Northern Africa we find, that the impact of changes in land use management (HANPPluc) is the dominant driver (see also figure 10), especially in the overall period from 2000 to 2013.

Decomposition of NPPact on all land use types combined

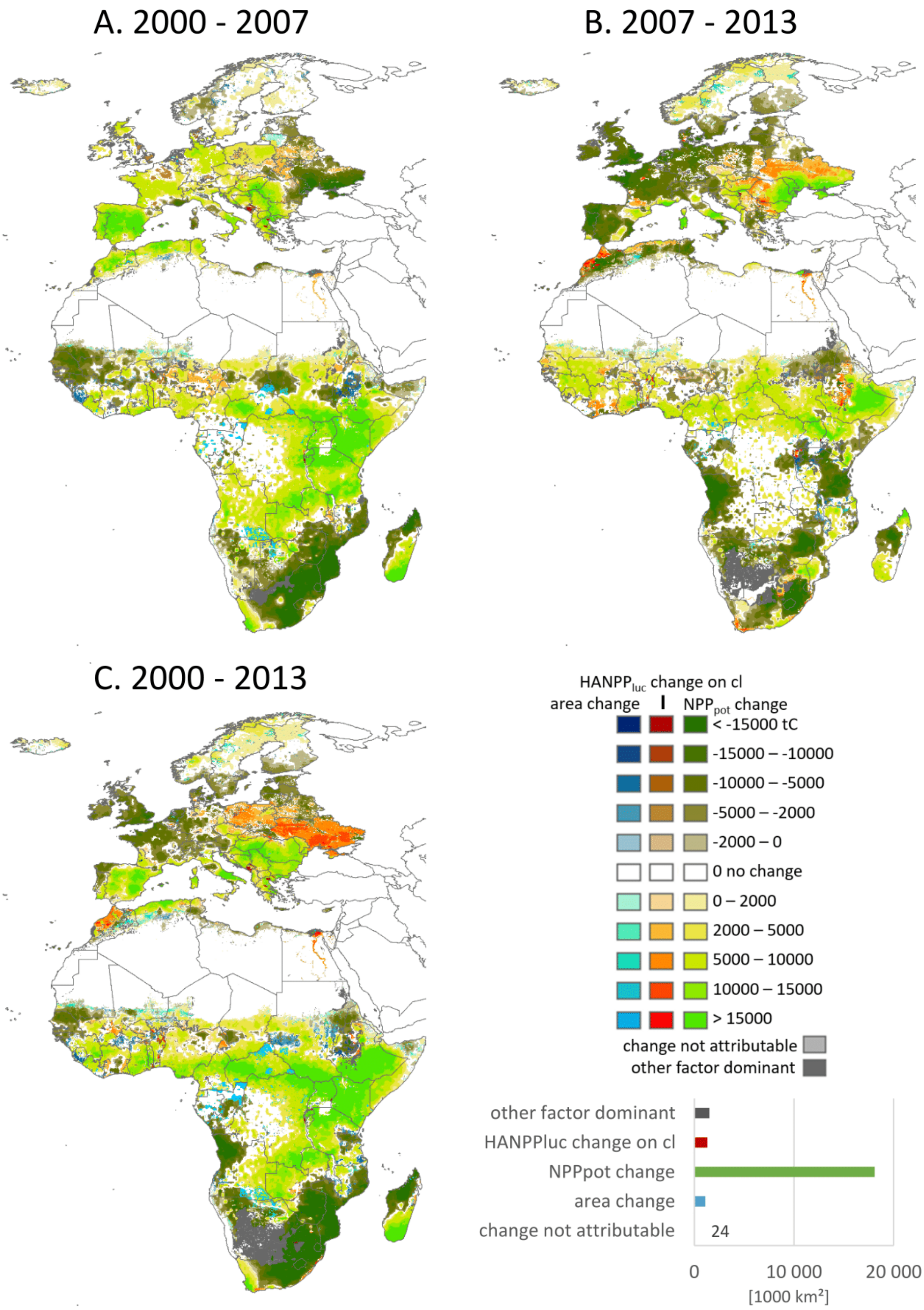

Figure 6: Contribution of dominant driver (area, NPPpot or cropland HANPPluc change) to change of NPPact in tC within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The effect "area" denotes the impact of land use type conversions on NPPact. NPPpot changes also affect all land use types and HANPPluc changes are only relevant on cropland, where land use management directly impacts NPPact. The histogram displays the area on which the respective factor contributes over 50% of the change of NPPact.

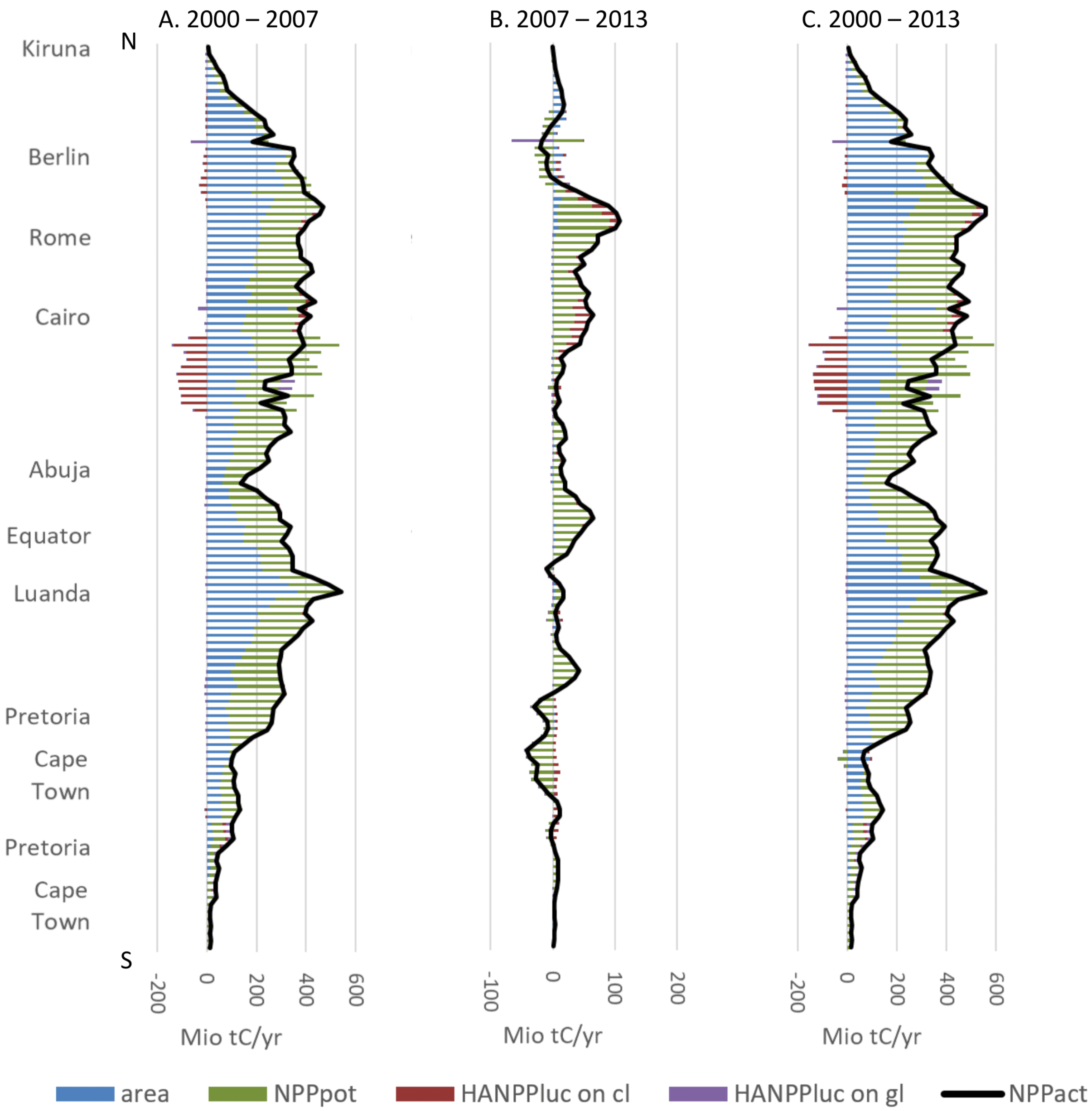

Figure 7: Contribution of area change, NPPpot change and cropland and grazing land HANPPluc change to change of NPPact in Mio tC/yr for 2000 to 2007 (A.), 2007 to 2013 (B.) and 2000 to 2013 (C.). Contributions are calculated over latitudinal bands over the European and African transect.

Decomposition of NPPact on cropland

Since cropland is the only land use type where HANPPluc is calculated in dynamic ways (e.g. takingt into account that fertilization and irrigation are to varying degrees used to increase productivity), an analysis for this land use type specifically is informative about the agricultural practice in a region.

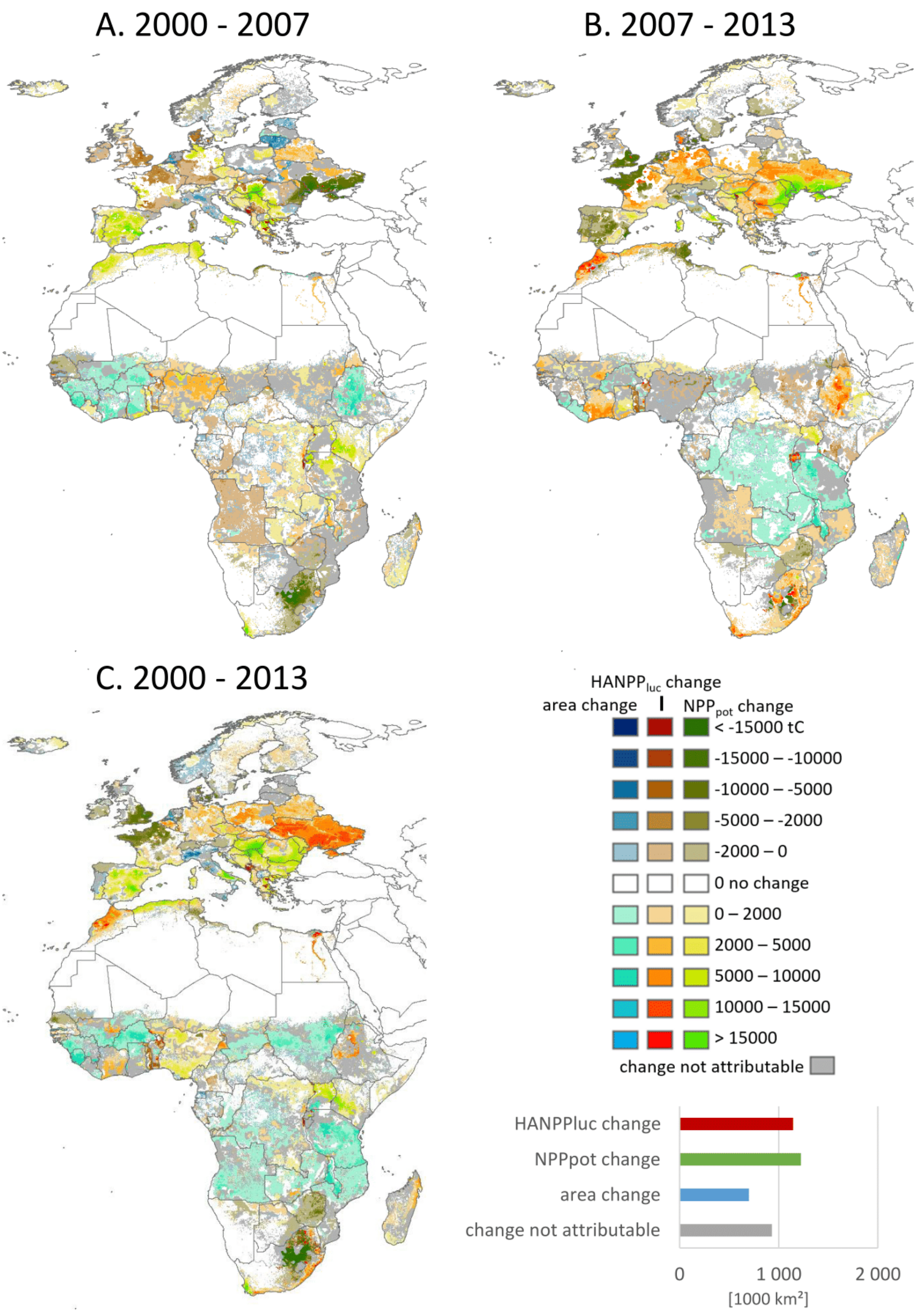

Figure 8: Contribution of dominant driver (area, NPPpot or HANPPluc change) to change of NPPact on cropland in tC within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the cropland area on which the respective factor contributes over 50% of the change of NPPact.

Expansion of cropland, as a means to create more cropland NPPact and, ensuing, biomass harvest, proves to be widely practiced on the African continent (see figure 11). This is already observed at the national-level analysis by (Fetzel, Niedertscheider, Haberl, Krausmann, & Erb, 2016). A reduction of cropland area occurs in some parts of Europe (in Italy, the Baltic States and Norway), which in consequence schows decreases cropland NPPact. Changes of HANPPluc have the greatest positive impact on NPPact on cropland in Ukraine, the Nile Delta and Morocco, but are rather inconsequential in Sub-Saharan Africa with the exception of South Africa (see Annex, figure 32). In Ukraine this rise in NPPact can be linked to a considerable increase in fertilizer use as reported by the FAO (FAOSTAT, 2018).

Decomposition of NPPeco

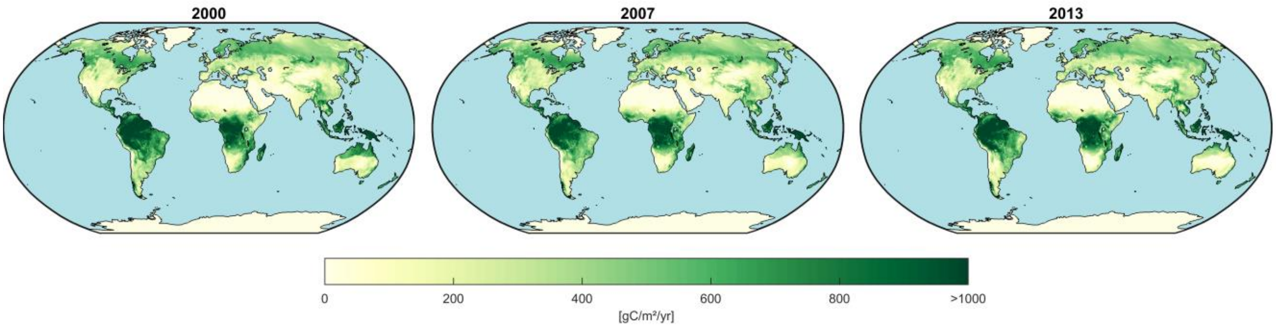

Figure 9: NPPeco [gC/m²/yr] for 2000, 2007 and 2013.

The decomposition of NPPeco dynamics (Figure 12) considers not only inputs of NPPact increasing measures, but also output intensity of land use systems by including HANPPharv.

On croplands (Figure 13) in Angola, the DR Congo and the Central African Republic an increasing harvest between 2000 and 2013 led to a slight decrease of NPPeco. Otherwise relevant in Africa is the expansion of cropland area and the fluctuation of NPPpot as a driver for NPPeco. In large parts of Europe, the change of NPPeco could not be attributed to one single factor, but figure 33 (see Annex) reveals the similar relevance of all factors and shows a clear process of cropland intensification in Ukraine.

NPPeco on grazing land (figure 14) proves to be heavily dependent on climatic fluctuations and area changes. Those changes are of greater magnitude than changes in the amount harvested, therefore the change of NPPeco is rarely attributed to changing HANPPharv in this analysis.

On forest land climatic fluctuations are also a very prominent driver of change (figure 15), but impact NPPeco in a lesser magnitude. Fluctuations of harvest are a driving force in some regions, with decreasing wood harvest leading to growth of NPPeco in Southern France, while Central and Eastern Europe display regions of decreasing NPPeco due to a rise in harvest activities.

Cropland

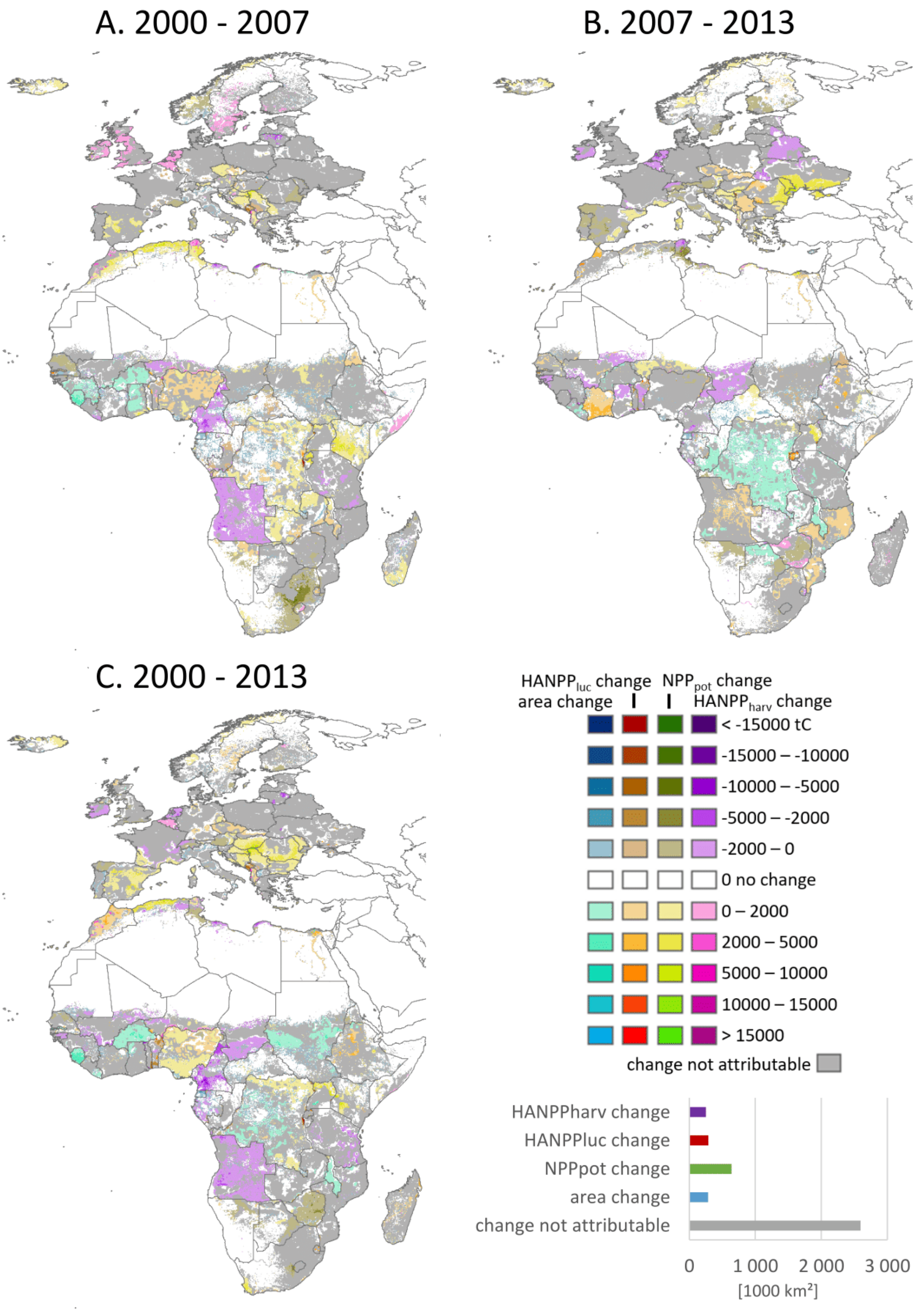

Figure 10: Contribution of dominant driver (area, NPPpot, HANPPluc or HANPPharv change) to change of NPPeco on cropland in tC within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the cropland area on which the respective factor contributes over 50% of the change of NPPeco.

Grazing land

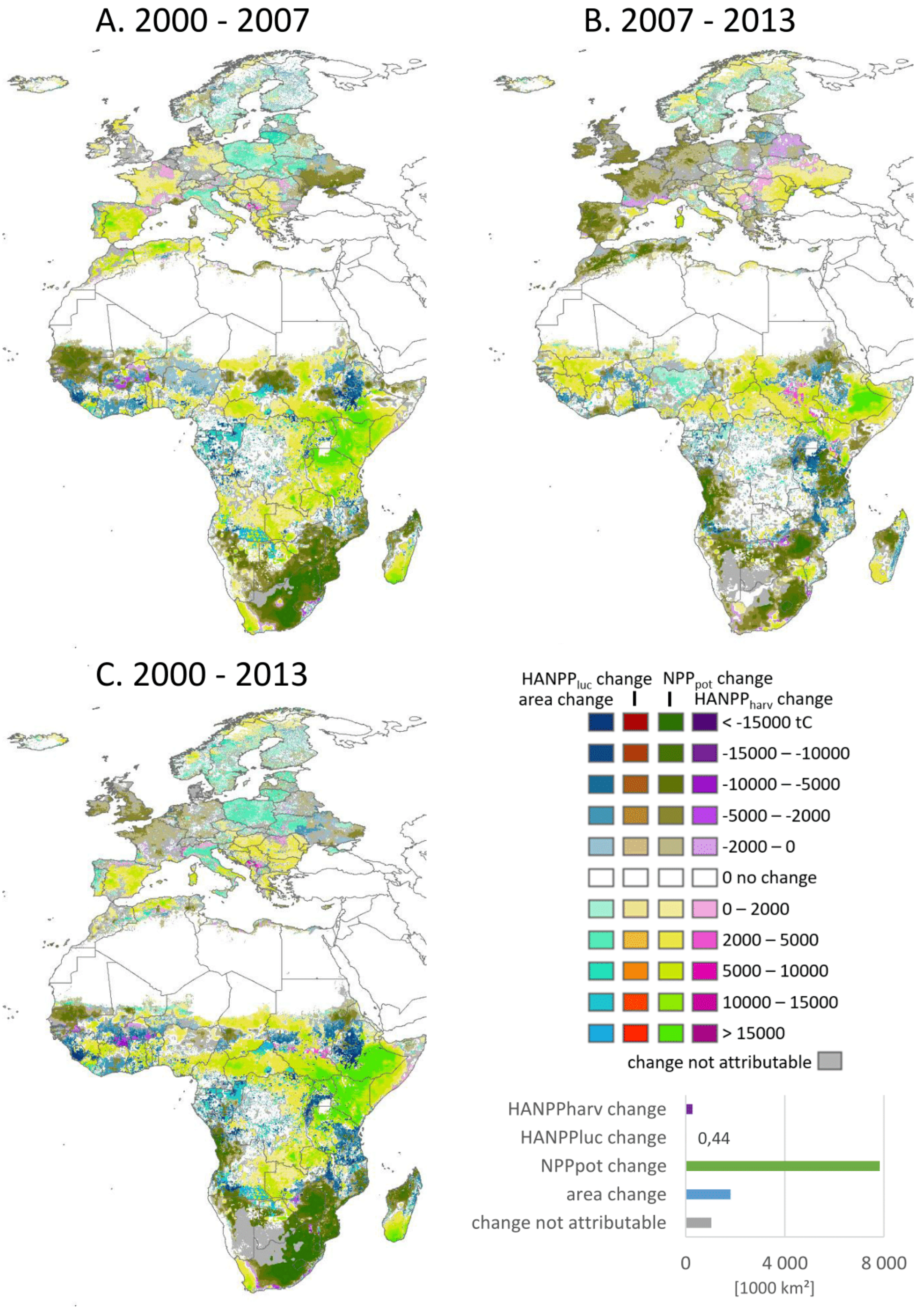

Figure 11: Contribution of dominant driver (area, NPPpot, HANPPluc or HANPPharv change) to change of NPPeco on grazing land in tC within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the grazing land area on which the respective factor contributes over 50% of the change of NPPeco.

Forest land

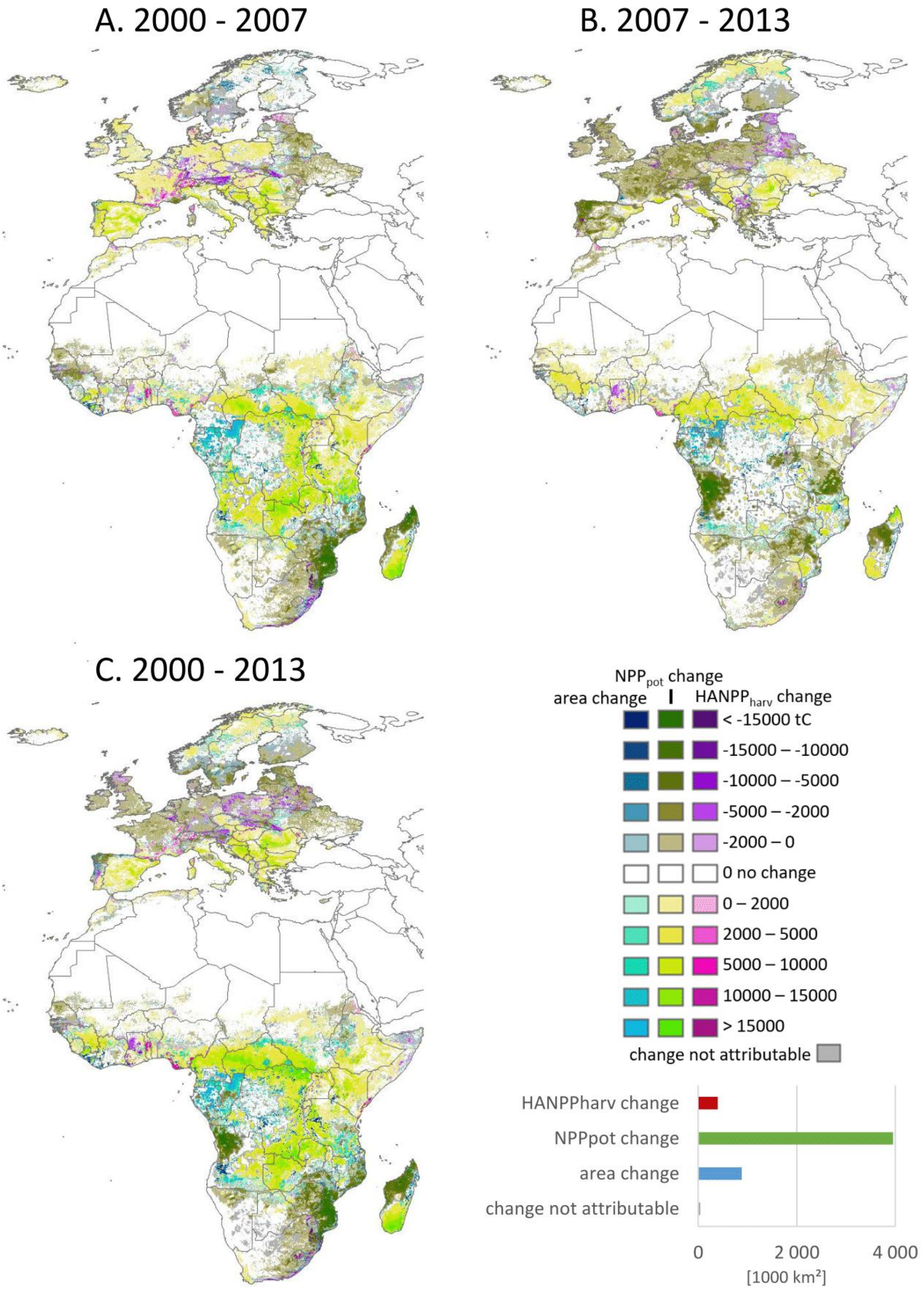

Figure 12: Contribution of dominant driver (area, NPPpot or HANPPharv change) to change of NPPeco on forest land in tC within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the forest land area on which the respective factor contributes over 50% of the change of NPPeco.

Decomposition analysis of HANPP on all land use types

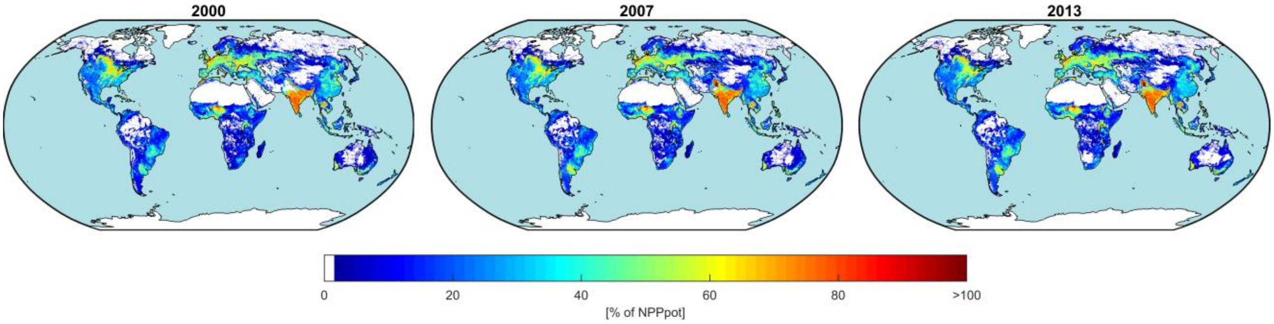

Figure 13: HANPP [% of NPPpot] for 2000, 2007 and 2013.

HANPP as an indicator for anthropogenic land-use intensity was decomposed to comprehend the nature of the applied land use management practice and distinguish between processes of intensification and efficiency enhancement by intentionally disregarding climatic changes as drivers. The pattern of HANPP is displayed inn Figure 16 for the periods of regard.

Figure 17 shows which general land use management trend on all land use types combined drives the development of HANPP, which shows mixed patterns of decrease and increase for both Europe and Africa during the given period 2000 to 2013. Decreases of HANPP in Europe’s South were driven by decreasing intensity and increasing efficiency. Belarus, Ethiopia and Kenia are countries with extensive areas characterised by intensification. Area changes of land use types are the main driver of HANPP only in some regions, mostly in Africa, in particular pronounce in Somalia and Kenia in the first half of the period. Further, well-delineated hotspots of intensity changes emerged in Ukraine and South Africa, but also in southern France

When distinguishing between the land use management on different land use types as driving forces for HANPP change (figure 18), land use management changes on grazing land are shown to be driving HANPP on large parts of the African continent, mostly contributing to HANPP within a ± 5 percentage point range. Also driving HANPP in the same magnitude is land use intensification on forest land in the DR Congo and Scandinavia. Northern Africa and Europe exhibit occasional regions, where cropland management drives the overall HANPP trajectory, but cropland management seems to impact HANPP considerably less frequently than management of grazing land and forest land.

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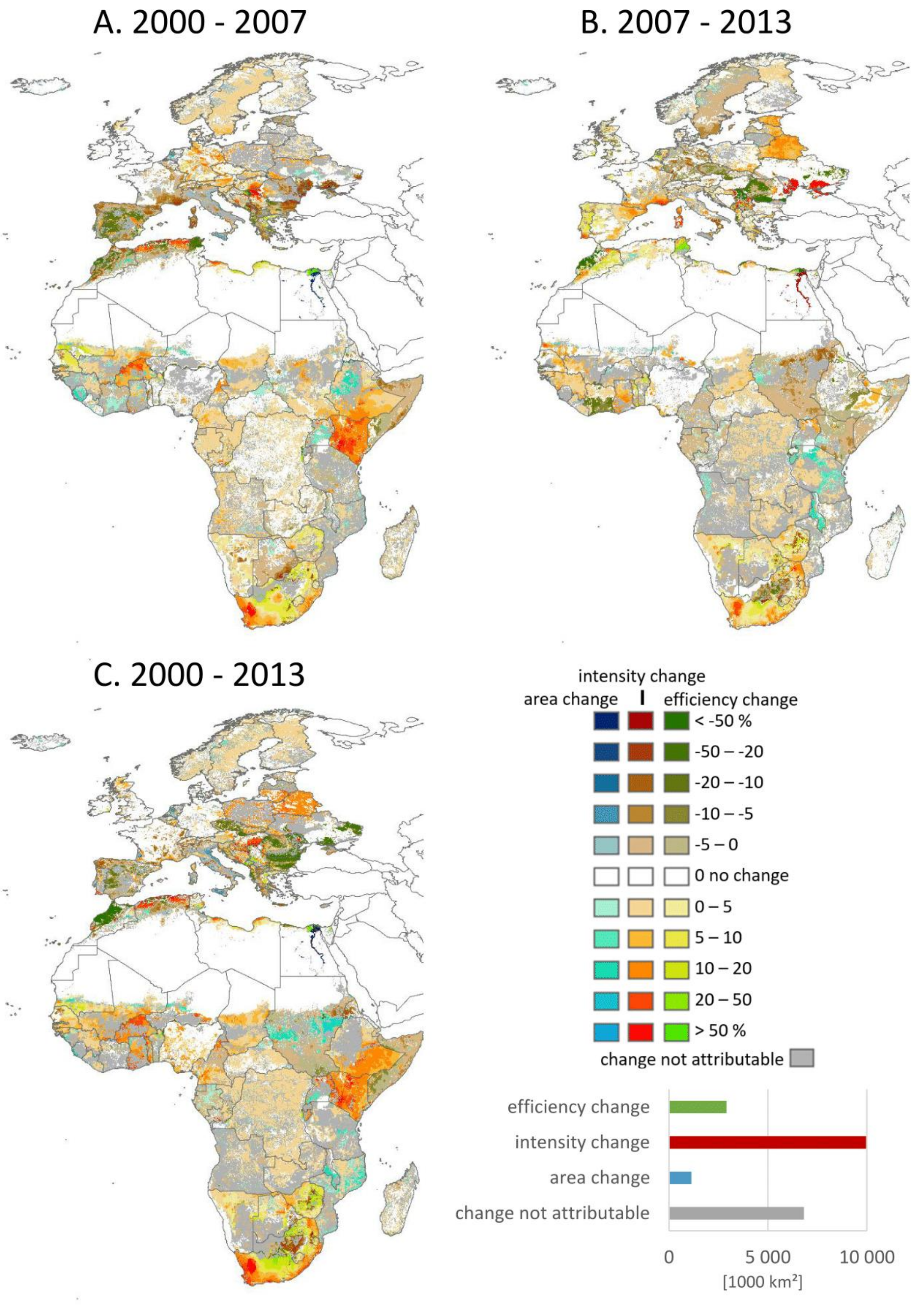

Figure 14: Contribution of dominant driver (area, intensity or efficiency change) to change of HANPP on all land use types combined in % within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the area on which the respective factor contributes over 50% of the change of HANPP.

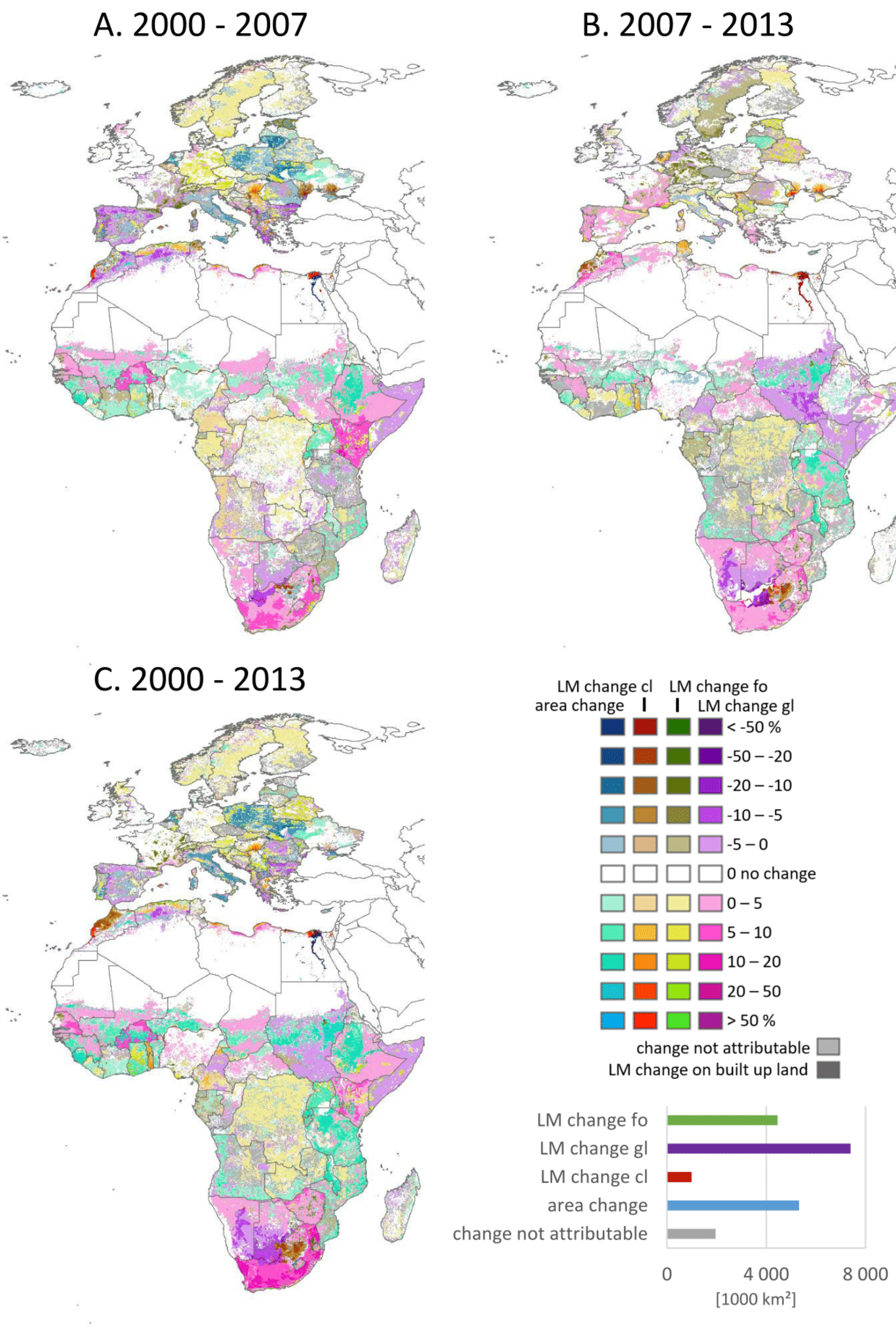

Figure 15: Contribution of dominant driver (area change or land use management (LM) change on cropland, grazing land or forest land) to change of HANPP on all land use types combined in % within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the area on which the respective factor contributes over 50% of the change of HANPP.

Decomposition of cropland HANPP (figure 19) reveals regions where area, intensity and efficiency effects all drive HANPP equally. A separate decomposition of land use changes for the land-use categories allows to scrutinize general patterns of change (Figures 19-21).-While Area changes are particularly important for cropland, but here all three components are of similar size, intensity changes dominate grazing land and forestry dynamics. Owing to the more confined spatial extent of cropland, regions with one of the three components dominating on cropland changes are smaller, while dominant changes of the other two land-use categories cover almost the entire transect.

Cropland intensification is confirmed as a main process between 2007 and 2013 in Ukraine, but also in Hungary and Serbia for 2000 to 2013. Sweden experienced an increase in efficiency, while Italy's cropland HANPP decrease is driven by a decrease in cropland area. This analysis confirms that growth of agriculture in Africa is mainly accomplished by area expansions.

For HANPP on grazing land the drivers of the greatest magnitude are intensification in Ethiopia, Kenia and Burkina Faso. South Africa's increase in grazing land HANPP between 2000 and 2013 is mainly driven by intensity increases in the West and efficiency decreases in the East. Grazing land area changes are mostly of influence on HANPP in Scandinavia, Poland and Northern Italy.

HANPP on forest land is predominantly driven by fluctuations in harvest intensity, area changes are rarely of relevance. Overall this land use type does not experience great fluctuations in HANPP, main driving forces contribute to change only within a $\pm$5 percentage point range, but some intensity fluctuations leading to HANPP changes above 5% can be found in Ghana and scattered across Europe.

Cropland

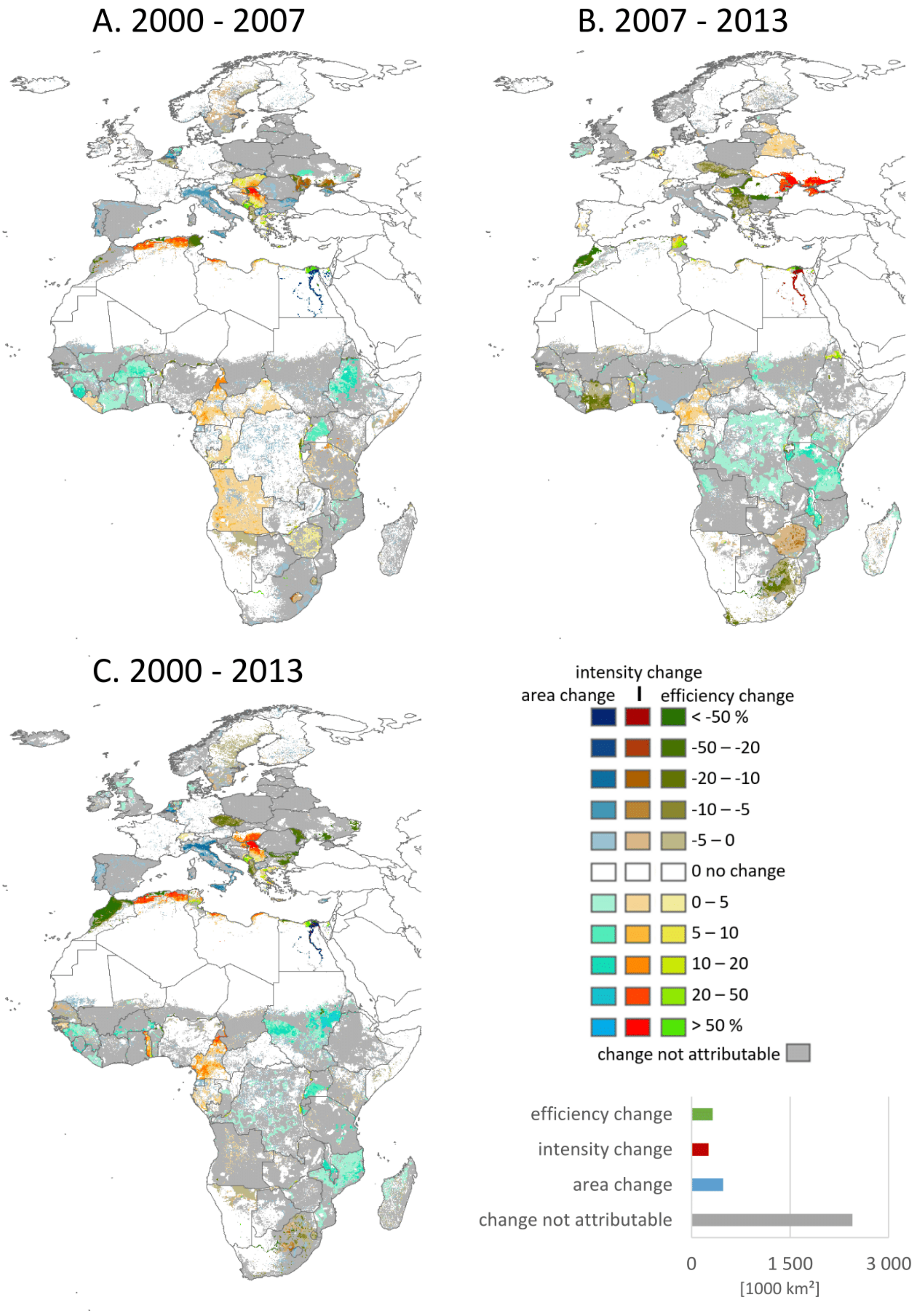

Figure 16: Contribution of dominant driver (area, intensity or efficiency change) to change of HANPP on cropland in % within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the cropland area on which the respective factor contributes over 50% of the change of HANPP.

Grazing land

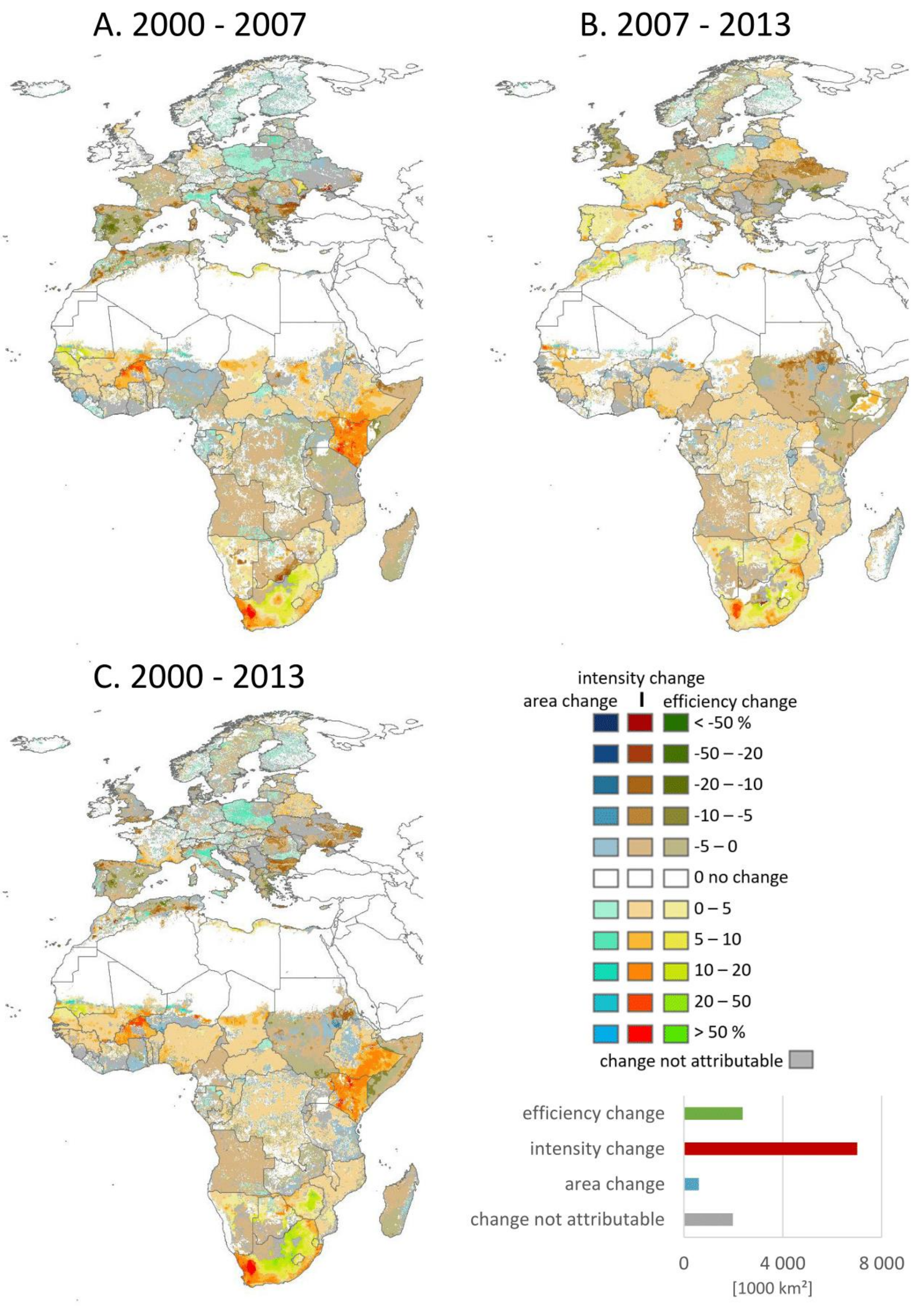

Figure 17: Contribution of dominant driver (area, intensity or efficiency change) to change of HANPP on grazing land in % within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the grazing land area on which the respective factor contributes over 50% of the change of HANPP.

Forest land

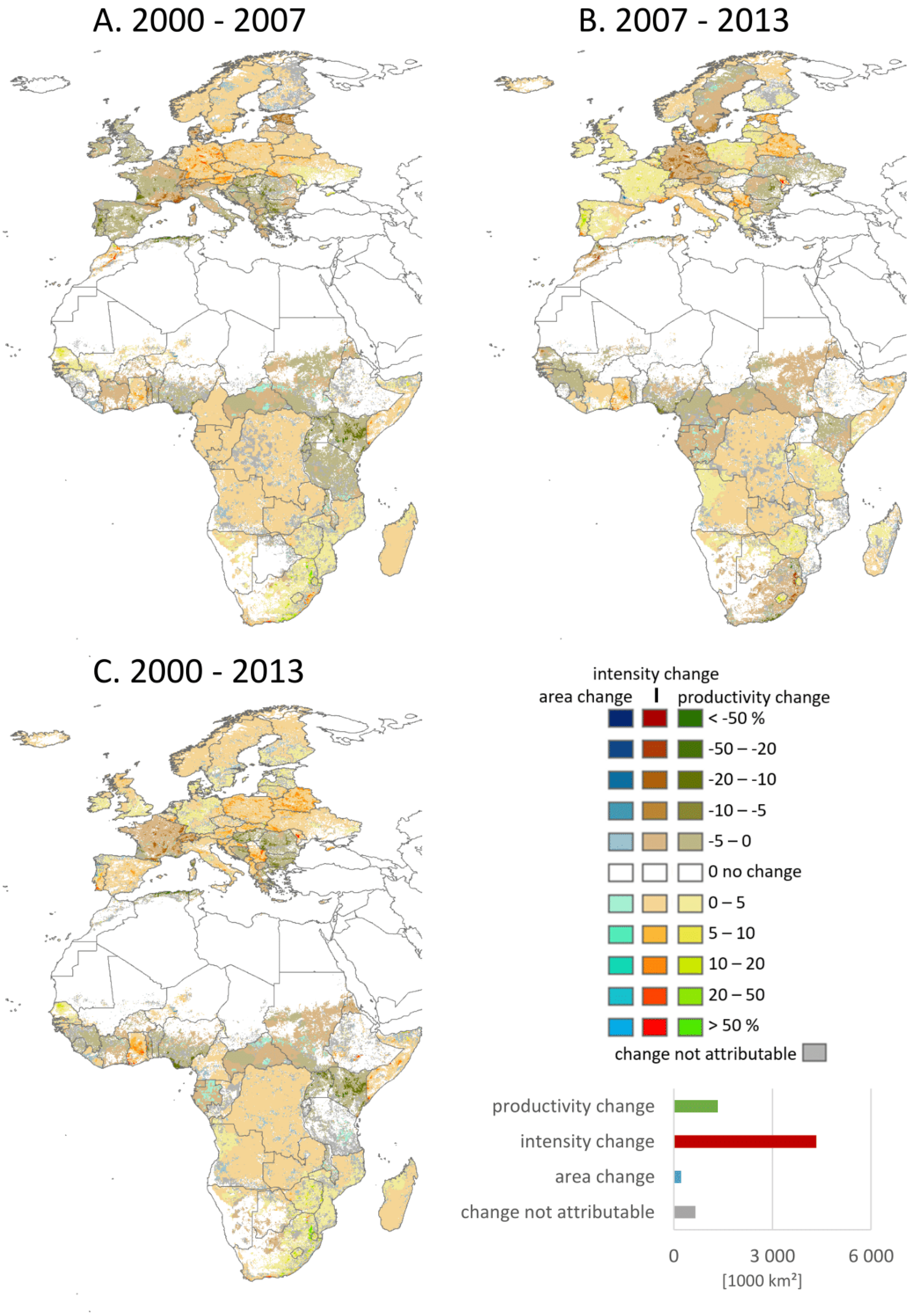

Figure 18: Contribution of dominant driver (area, intensity or productivity change) to change of HANPP on forest land in % within a 5x5min grid cell for A. 2000-2007, B. 2007-2013 and C. 2000-2013. The histogram displays the forest land area on which the respective factor contributes over 50% of the change of HANPP.

Trends in selected countries

In order to scrutinize land-use dynamics in combination with economic, social and institutional drivers of change, we combine trends of land use and corresponding biomass flows with indicators attributed to the socio-economic status of a country. These indicators include the area equipped for irrigation (in percent of cropland), population and economic activities in the sectors agriculture, hunting, forestry and fishing (ISIC A-B).

Land-use variables cover area changes for the four main land categories built-up area, cropland, grazing land and forest land. Unproductive areas like barren or permanent snow and wilderness areas were neglected in this analysis. Biomass flows show trends in NPPpot, NPPact, NPPeco, HANPPharv and HANPP. Additionally we show the development of HANPP efficiency (HANPPeff) which is the ratio of HANPPharv to HANPPluc (K. H. Erb et al., 2009; Fetzel, Gradwohl, & Erb, 2014; Niedertscheider & Erb, 2014). HANPPeff can be interpreted as an efficiency measure of land use. To disentangle the different contributions to NPPeco and HANPP changes over time, we present the results of the decomposition analysis on country level.

For this analysis we have chosen four countries of the BACI transect: Ukraine, Togo, Ethiopia and South Africa. The regions have been selected on basis of the decomposition analysis which revealed interesting trends in NPP and land use over the periods of regard. The discussed period varies, for Ethiopia and South Africa we refer to 1960 to 2013, for Ukraine and Togo to 2000 to 2013.

Ukraine

From 1960 to 1990 the Ukraine showed no noteworthy area changes of land use, despite a slight decrease of cropland area, which is more and more equipped for irrigation. Between 1980 and 1990 we find an increase of harvested NPP, associated with remarkable increase of HANPPeff. In the following decade, from 1990 to 2000, we see the drastic consequences of the fall of the Soviet Empire. This instituional changes resulted in a sharp decline of cropland area. Land abandonment led to a distinct increase of grazing land. The increment of area equipped for irrigation stagnated in this period. Also the forest area, until this point quite stable, declined. The GDP associated with agricultural activities (ISIC A-B) declined dramatically from over 400,000 USD/cap to around 100,000 USD/cap. Even the total population of the Ukraine declined by more than 5%, underpinning the tense situation of this era.

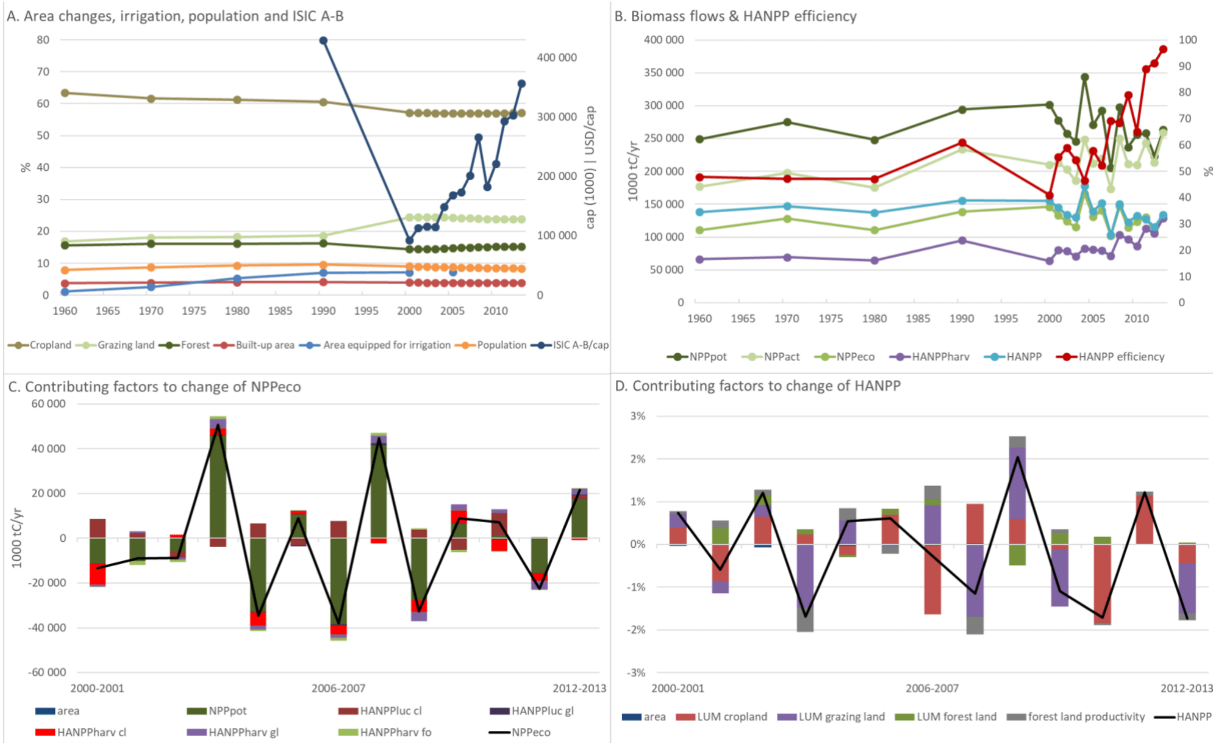

Figure 19: Country specific data on development of land use areas, irrigation (as % of cropland), population and GDP (A.) and on biomass flows, and HANPP efficiency (B.) for Ukraine. C. depicts the contributions of climatic change (NPPpot change) versus human induced land cover change (area change) and land use management change (HANPPluc and HANPPharv change on cropland (cl), grazing land (gl) and forest land (fo)) to annual change of NPPeco in tC/yr for the period 2000 to 2013. D. depicts the contributions of human induced land cover change (area change) and land use management change on cropland, grazing land and forest land to annual change of HANPP for the period 2000 to 2013 in %.

Looking at biomass flows, we find the consequences of this change in the loss of harvested NPP as well as in the decrease of HANPPeff, in both cases below the levels of 1960. In the years after this break land use areas stabilized. Harvested NPP and HANPPeff increased in this period, the latter one in impressive manner, presumably due to aforementioned increases in fertilizer application, a process that is typical industrialization processes in agriculture (Gingrich et al., 2015a; Niedertscheider, Kuemmerle, Müller, & Erb, 2014). This increase came along with a considerable boost of land-based economic activities (ISIC A-B), indicating a clear recovery and industrialization of the agricultural system in the Ukraine after 2000.

Fluctuations of NPPeco in the period 2000 – 2013 mainly depended on the variation of NPPpot, indicating a prevalence of climate relative to human influences, for many ecosystem processes. NPPpot shows strong fluctuations, which also influences HANPP trajectories, usually in inverse ways (increase of NPP is associated with a decrease grazing contributions, for instance). Still we find the contributions of cropland management (expressed as HANPPluc and HANPPharv on cropland) to have considerable effect on NPPeco, especially from 2000 to 2001 and 2009 to 2011. Area changes play a minor role in the entire period 200-2013 when compared to management impacts.

HANPP varied between -2% and 2%, where the factors Land Use Management (LUM) on cropland and grazing land where the two most important factors, whereas area changes and forest related factors were marginal.

Togo

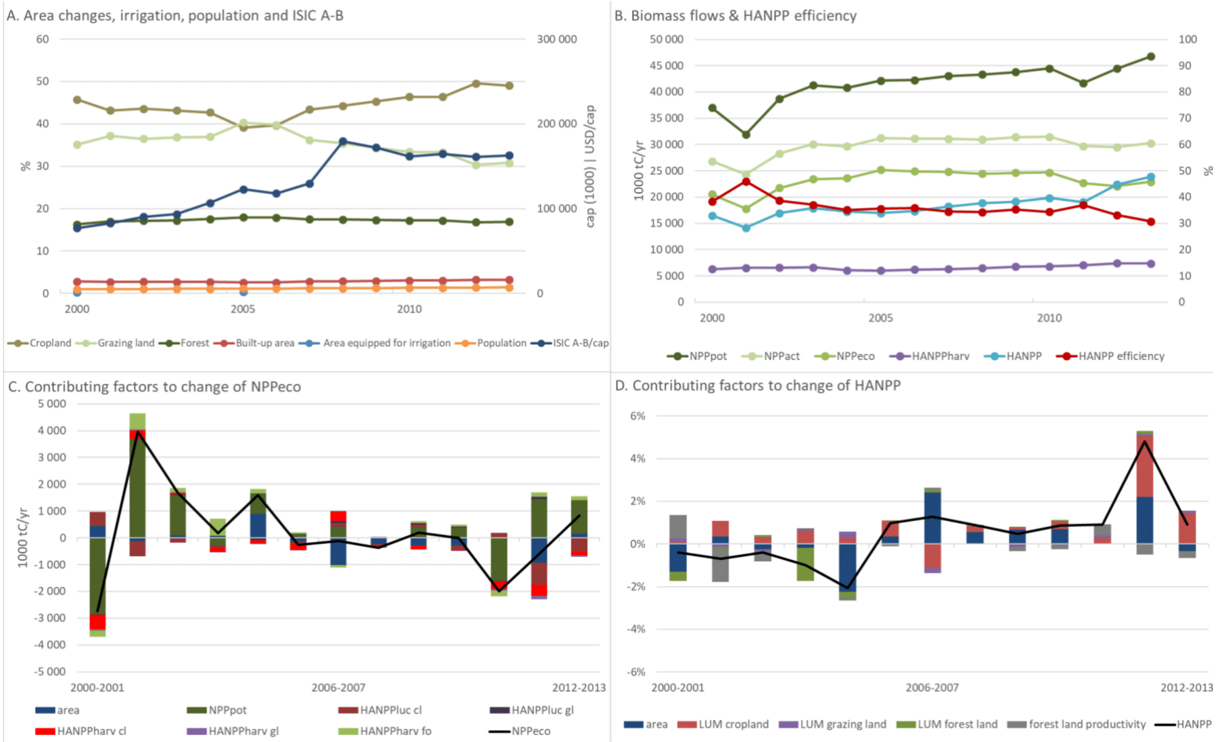

Figure 20: Country specific data on development of land use areas, irrigation (as % of cropland), population and GDP (A.) and on biomass flows, and HANPP efficiency (B.) for Togo. C. depicts the contributions of climatic change (NPPpot change) versus human induced land cover change (area change) and land use management change (HANPPluc and HANPPharv change on cropland (cl), grazing land (gl) and forest land (fo)) to annual change of NPPeco in tC/yr for the period 2000 to 2013. D. depicts the contributions of human induced land cover change (area change) and land use management change on cropland, grazing land and forest land to annual change of HANPP for the period 2000 to 2013 in %.

Togo showed an increase of grazing land in the years 2000 – 2005 of more than 5 points, a development at the expense of cropland. This trend reversed in 2005, the year of the end of the dictatorship, and in 2012 cropland area outstripped the level of 2000. Forest area as well as built-up area showed no specific trend over the whole period, while population increased by 42%. In the first six years, land-based economic activities (ISIC A-B) increased continuously, stopping in 2005. Only two years later, in 2007, when the first national elections were held, land-based economic activities (ISIC A-B) increased tremendously by nearly 50,000 USD/cap. From that time on, land-based economic activities (ISIC A-B) started to decline and stabilized in 2011.

Besides NPPpot and HANPP, which rise more or less constantly over the years (NPPpot: 26%, HANPP: 42%), biomass flows are more or less stable with two exceptions. The decline of NPPpot from 2000 to 2001 may be a result of the decrease of annual precipitation from 1961 to 2001 (Djaman et al., 2017). From 2010 to 2011, we again find a significant decline of NPPpot, which is also reflected in NPPact and NPPeco. HANPPeff shows two small peaks in 2001 and 2011, but besides these exceptions HANPPeff decreased constantly over the years. This is a strong sign for agricultural stagnation, i.e. intensification processes in terms of input-output intensity playing only a negligible role. Rather, production increase are almost solely a consequence of cropland expansion and the replacement of highly productive natural vegetation with agricultural systems. Indeed, area changes are mostly responsible for HANPP trajectories (Figure 26D).

In contrast, NPPpot dynamics played a strong role for the dynamics of NPPeco in the years 2001 and 2011. In contrast to NPPpot, influenced solely by environmental conditions, land-use area changes played a minor role. Exceptions are the pronounced effects in the years 2005, 2007 and 2012, where conversions between cropland and grazing land took place. Changes in NPPeco due to harvest can be linked mainly with cropland areas, while in 2002 also forest areas play a major role.

The main factors contributing to HANPP variations are area changes and land use management on cropland. HANPP decrease in 2005 and HANPP increase in 2007 due to area change may be linked to the political events in these years and warrant further scrutiny.

Ethiopia

Figure 21: Country specific data on development of land use areas, irrigation (as % of cropland), population and GDP (A.) and on biomass flows, and HANPP efficiency (B.) for Ethiopia. C. depicts the contributions of climatic change (NPPpot change) versus human induced land cover change (area change) and land use management change (HANPPluc and HANPPharv change on cropland (cl), grazing land (gl) and forest land (fo)) to annual change of NPPeco in tC/yr for the period 2000 to 2013. D. depicts the contributions of human induced land cover change (area change) and land use management change on cropland, grazing land and forest land to annual change of HANPP for the period 2000 to 2013 in %.

The most noticeable land use area change in Ethiopia in the period 2000 to 2013 was the decline of grazing land to the benefit of cropland. In these years Ethiopia faced a remarkable population growth of 43%. ISIC A-B/cap fell slightly in the first two years and then started to grow exceptionally in 2002, the year when the Eritrea–Ethiopia Boundary Commission agreed upon a "final and binding" verdict after the Eritrean–Ethiopian War (1998-2000). In 2010 this trend stopped for one year and ISIC A-B/cap declined considerably, coinciding with the Ethiopian general election. In the next two years, ISIC A-B/cap again increased rapidly followed by a stagnation in 2013.

Biomass flows increased slightly and more or less constantly over the years with some deviations of NPPpot (2002 and 2009), causing fluctuations in NPPact and NPPeco. HANPPharv and HANPPluc did not show these fluctuations; this can be taken as an indication that at larger scales, reductions in productivity that result in reduced harvest are compensated by increased harvest in other regions of the country. Harvested NPP showed a slight increase over the 13 years. HANPPeff increased until 2002, but then declined substantially in the next two years, followed by a constant, albeit small, increase thereafter.

NPPeco changes were attributed mostly to variations of NPPpot, other factors played only a minor role. Changes in HANPP were mainly related to land-use management, especially on grazing land and cropland. Area changes also played an important role, especially in the years 2003 and 2004, when cropland increased considerably at the expense of grazing land. While management is an insignificant factor in forested areas, productivity of forested land has some influence on HANPP variations in some years, e.g. 2002 and 2010.

South Africa

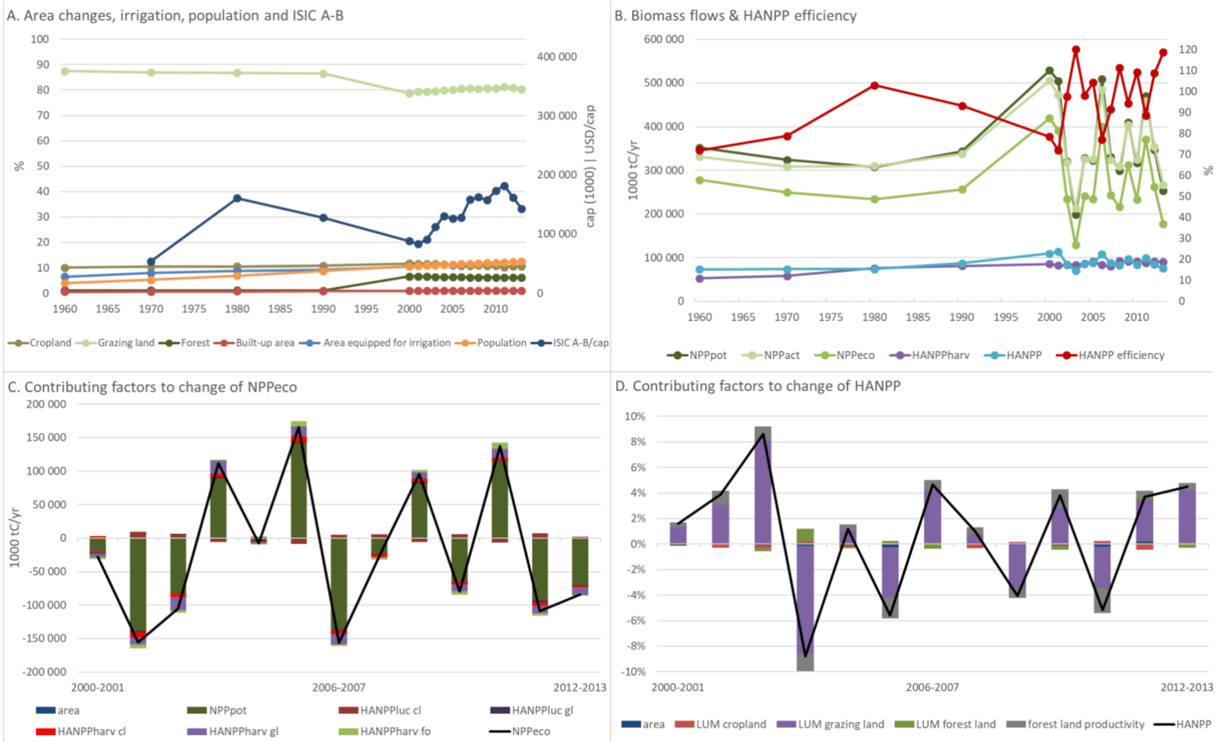

Figure 22: Country specific data on development of land use areas, irrigation (as % of cropland), population and GDP (A.) and on biomass flows, and HANPP efficiency (B.) for South Africa. C. depicts the contributions of climatic change (NPPpot change) versus human induced land cover change (area change) and land use management change (HANPPluc and HANPPharv change on cropland (cl), grazing land (gl) and forest land (fo)) to annual change of NPPeco in tC/yr for the period 2000 to 2013. D. depicts the contributions of human induced land cover change (area change) and land use management change on cropland, grazing land and forest land to annual change of HANPP for the period 2000 to 2013 in %.

In the period 1960 to 1990 the ratio of land use types was quite stable. The area equipped for irrigation increased by 2 percent points from 7% to 9% of cropland. Economic activities in agriculture and related sectors increased from 1970 to 1980 and then decreased in the next decade. Population more than doubled from 1960 to 1990. In these years NPPpot showed firstly a decline until 1980, followed by an increase until 1990, reaching approximately the same level as in 1960. NPPact and NPPeco followed this pattern. Both, HANPPharv and HANPP, showed a slight increase in these 30 years. Similar to ISIC A-B/cap HANPPeff was rising until 1980 and then declining in the next 10 years.

The decade 1990 until 2000 represented a turning point in the history of South Africa: the end of the Apartheid regime and the first general elections for all citizens in 1994 (Niedertscheider, Gingrich, & Erb, 2012). In these 10 years grazing land reduced significantly, while forested areas increased. This may be interpreted as bush encroachment due to natural succession after the abandoning of pastures. The decline of ISIC A-B/cap followed the trend of the previous decade. NPPpot boosted dramatically by more than 50%, while harvested NPP only increased by 6%. Again, HANPPeff followed a complementary pattern like ISIC A-B/cap and continued the decline of the 80s. From 2000 to 2013 the land use arrangement kept more or less stable. Population still was growing but quite slower than in the

20th century. After 20 years of decline ISIC A-B/cap started to raise significantly and outperformed the status of 1980 in 2011. But in the next two years ISIC A-B/cap again started to fall. Biomass flows, especially NPPpot (and related NPPact and NPPeco), showed dramatic oscillations, with a noticeable minimum in 2003. In this year also HANPP had its lowest value for the whole 53 years. HANPPeff was rising over the period from 2000 to 2013, showing distinct fluctuations.

NPPeco changes mainly were driven by changes in NPPpot in South Africa, the second most important factor, even though far behind, was harvested biomass on grazing lands. The most important factor impacting HANPP was land-use management on grazing land, but also productivity in forested areas played some role.

4. Resumé and further steps

In this report we present an analysis of global land-use and related biomass-flows at a five minutes (ca. 10x10 km2 at the equator) resolution for the period 1900-2013. From the year 2000 onwards, the dataset is annual and allows to trace land use and land cover changes at a very high temporal detail. An approach was developed to decompose the observed changes in land use and biomass flows in ecosystems and society. This approach allowed to assess the individual weight, and importance, of natural drivers as well as land use for the observed changes. Land use effects could be split into area effects, i.e. effects of land-cover or land-use conversions, and intensity effects (management effects). These results and data sets are built to contextualize directly the results obtained from the BAC-index and its underlying streams.

The data sets here allows to integrate the socio-economic dimension of biosphere atmosphere changes into BACI, and particularly to test the ability of BACI to detect changes in the biosphere relevant for land use and thus socioeconomic processes. NPP flows, which are a key input for the HANPP calculation, can be directly related to many ecosystem processes. In the future task of WP7 of the BACI project, the changes described here, based on a decomposition analysis, will be linked to BACI and data stream such as, e.g. GPP, FaPAR, or water use efficiency. Such an endeavour will allow distinguishing natural from “human” induced changes and thus facilitating the interpretation of changes observed in BACI products. The short, decadal time series (2000-2013), now developed to complement the centennial data presented in D7.2., will thus allow to better understand “change” itself, for instance, how it needs to be defined differently for natural and socioeconomic processes, and how these two entities interrelate. Furthermore, the long time series (1900-2010), systematically linked to the short one (2000-2013), allows to contextualize current land-use changes, in terms of magnitude, frequency and velocity of change, with changes that occurred in the past century.

Our findings on HANPP and its drivers suggest that land-use intensity changes are dominating the recent land use trends in most regions. Area changes, in contrast, play a strong, but more geographically confined role in only a few world region (predominantly the developing countries of Sub-Saharan Africa). Harvest dynamics, in particular of grazing and to a lesser extent, forestry, are particular important. Institutional changes play a key driving role, as the example of the Ukraine, South Africa or Togo reveal. This indicates that Earth Oberservation tools are not complete if they do not take such effects into account (for instance, see (K.-H. Erb, Fetzel, et al., 2016; K.-H. Erb et al., 2018; K.-H. Erb, Luyssaert, et al., 2016). The data set and analyses presented here will allow unravelling components of biosphere-atmosphere change that are beyond changes of spectral signals, but that occur at the heart of societal change.

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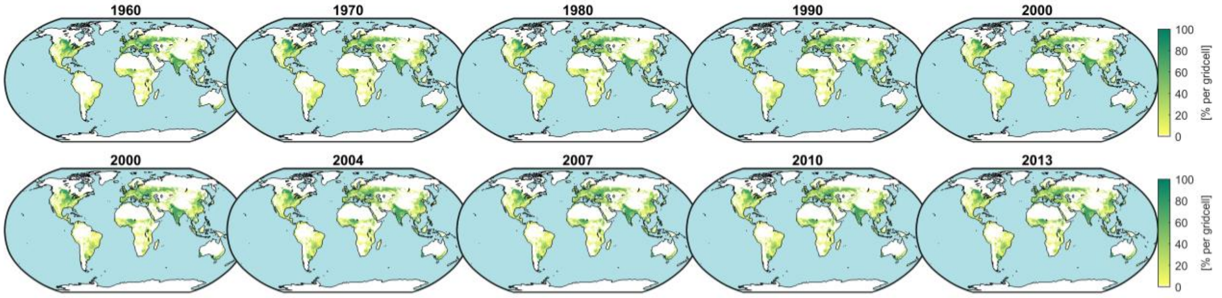
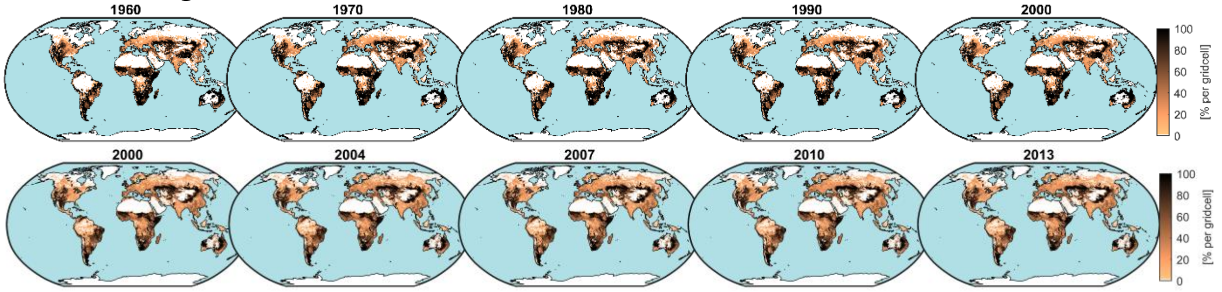
6. Annex

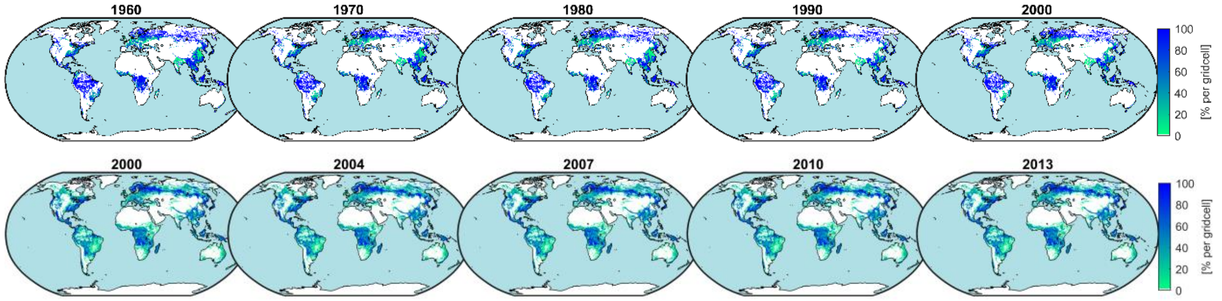
A. Cropland extent



B. Grazing land extent



C. Forest land extent



D. Built-up area extent

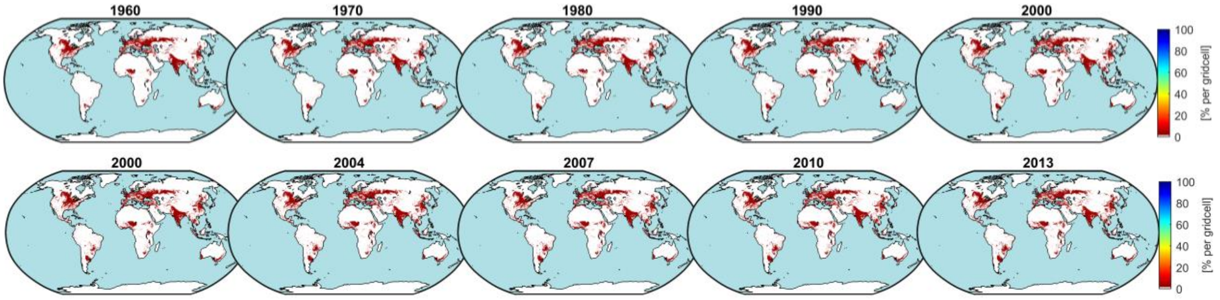


Figure 23: Time cuts for the years 1960, 1970, 1980, 1990, 2000 (two calculations), 2004, 2007, 2010, 2013 of A. cropland extent, B. grazing land extent, C. forest land extent and D, built-up area extent.

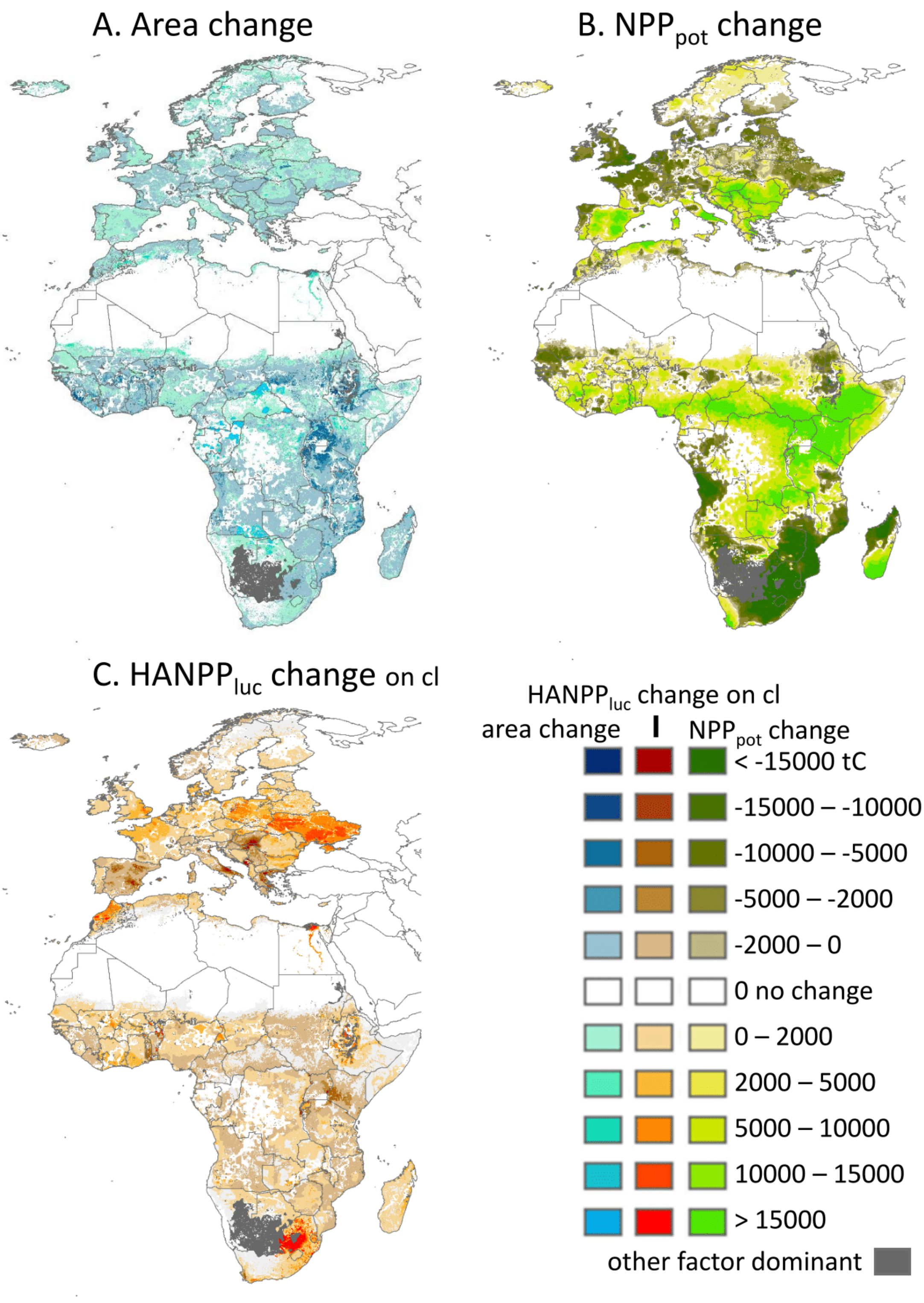


Figure 24: Contribution of area change, NPPpot change and cropland HANPPluc change to change of overall NPPact between 2000 and 2013 in tC.

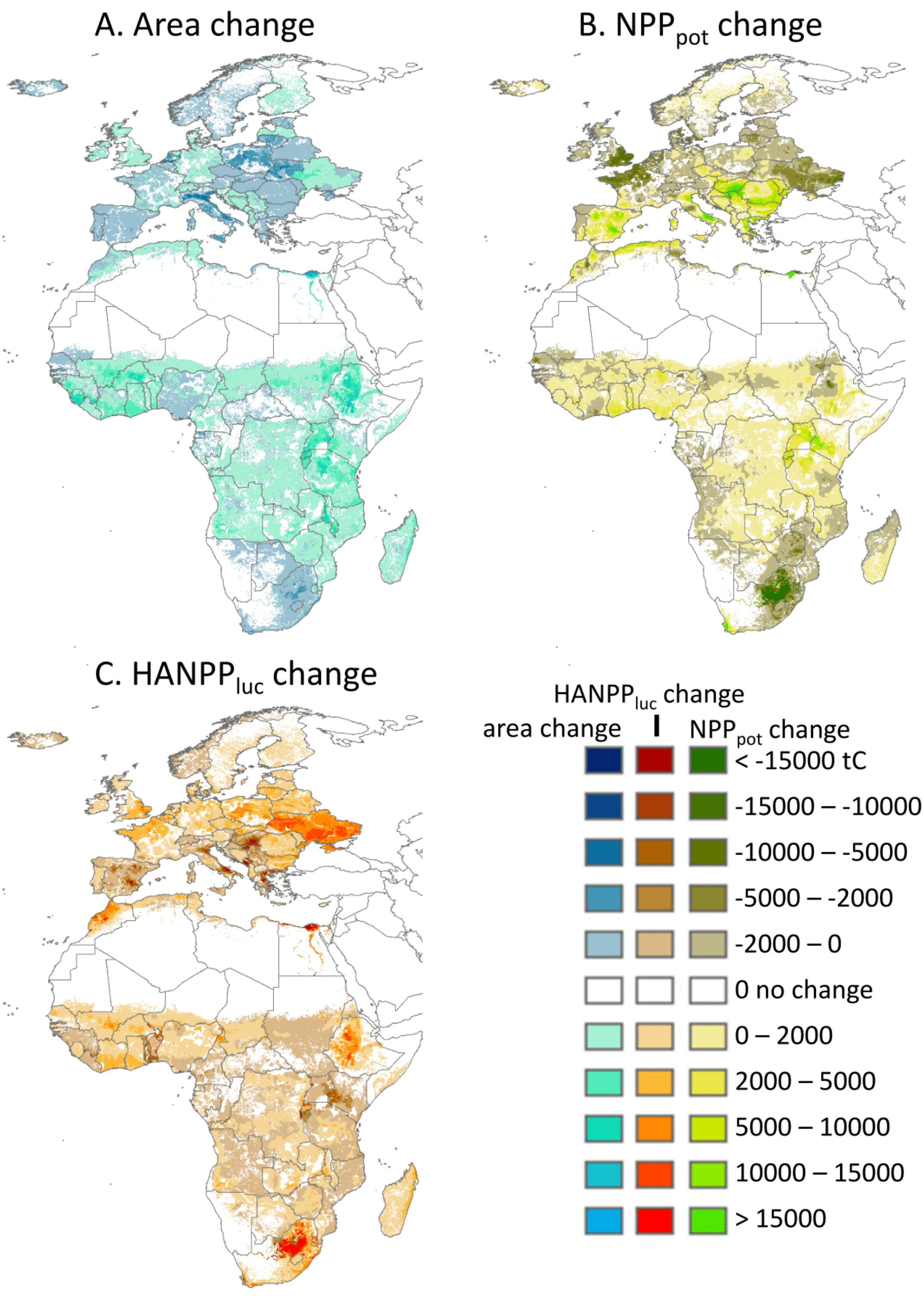


Figure 25: Contribution of area change, NPPpot change and land use cover change to change of NPPact on cropland between 2000 and 2013in tC.

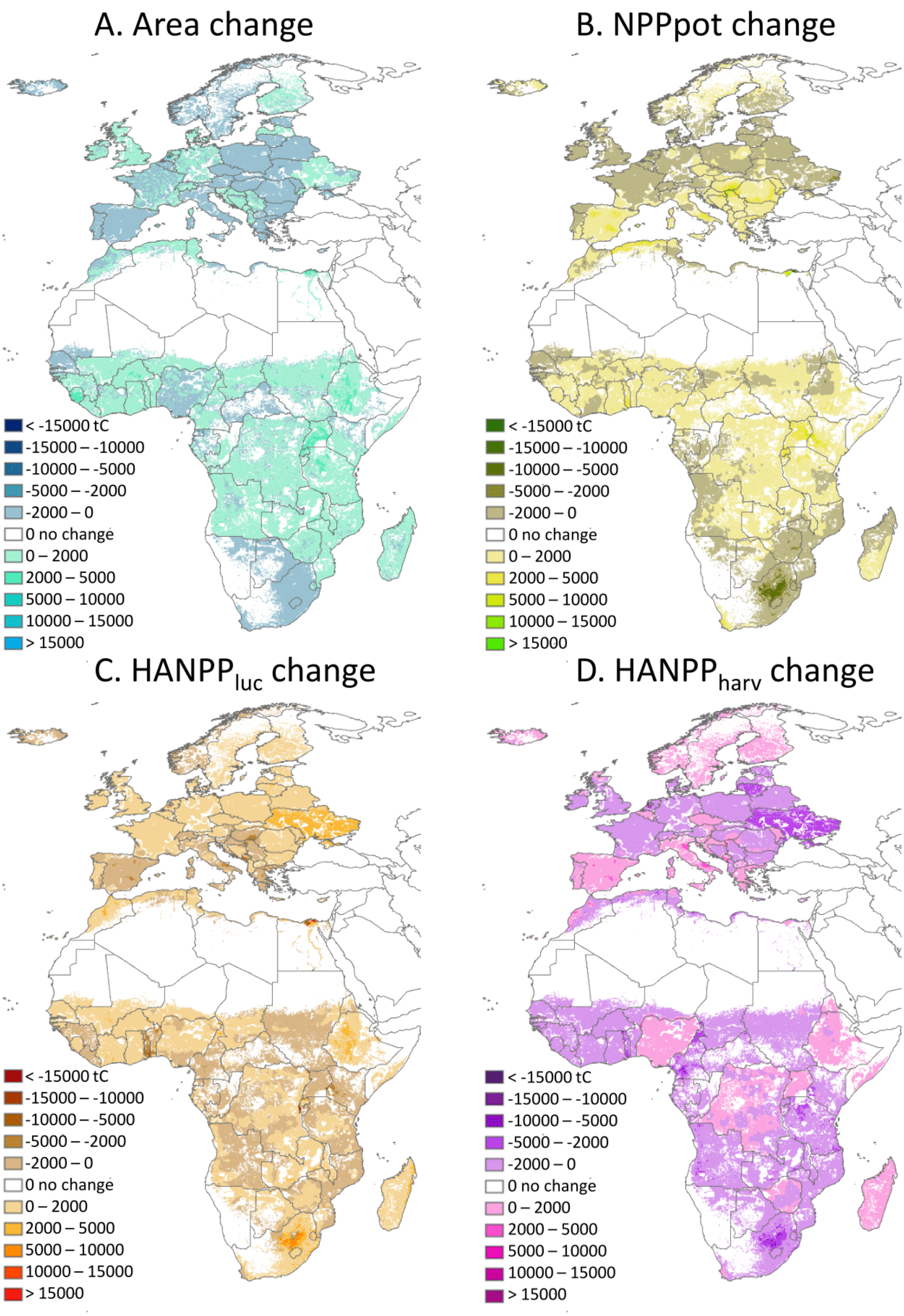


Figure 26: Contribution of area change, NPPpot change, HANPPluc change and HANPPharv change to change of NPPeco on cropland between 2000 and 2013 in tC.

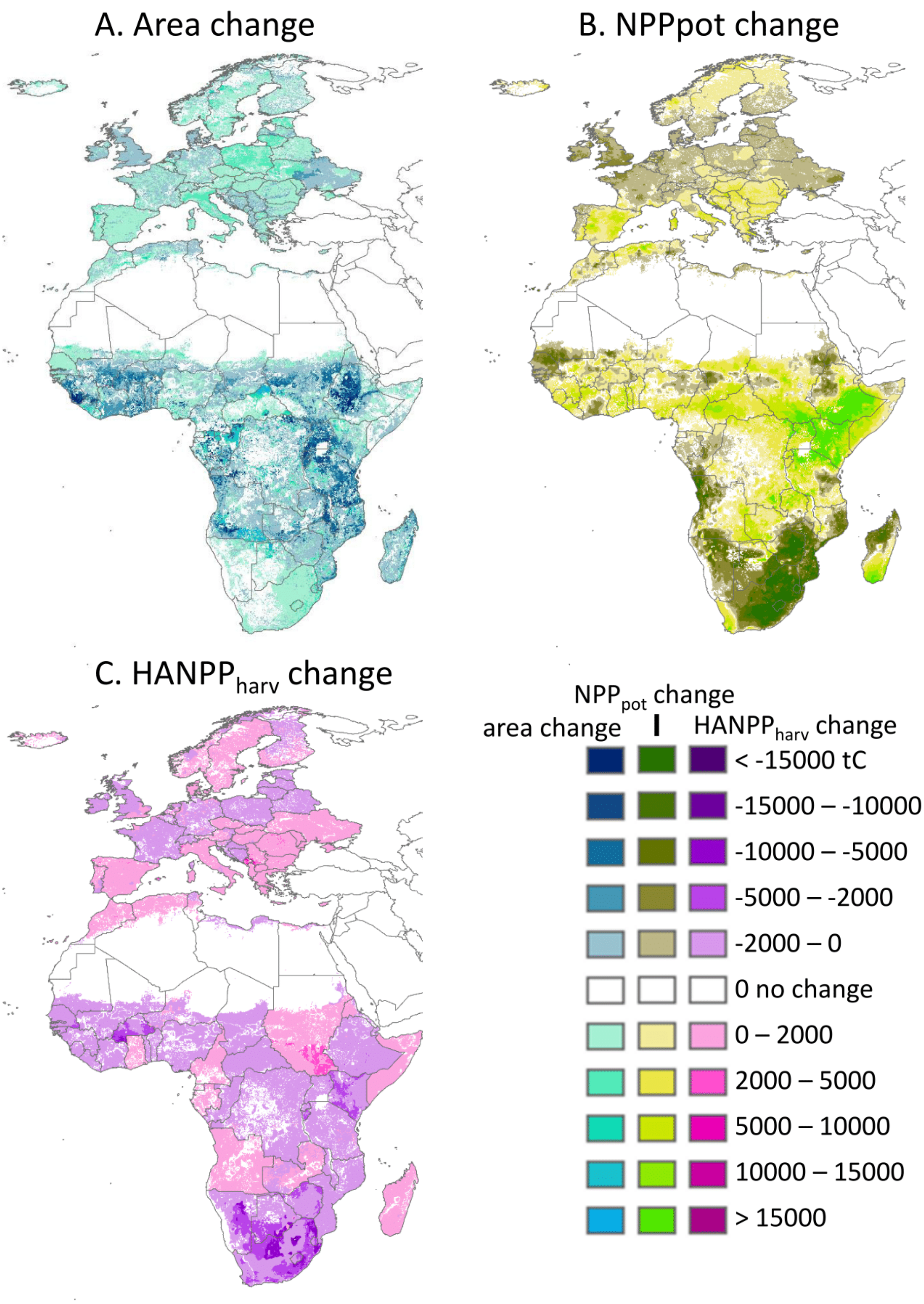


Figure 27: Contribution of area change, NPPpot change and HANPPharv change to change of NPPeco on grazing land between 2000 and 2013 in tC.

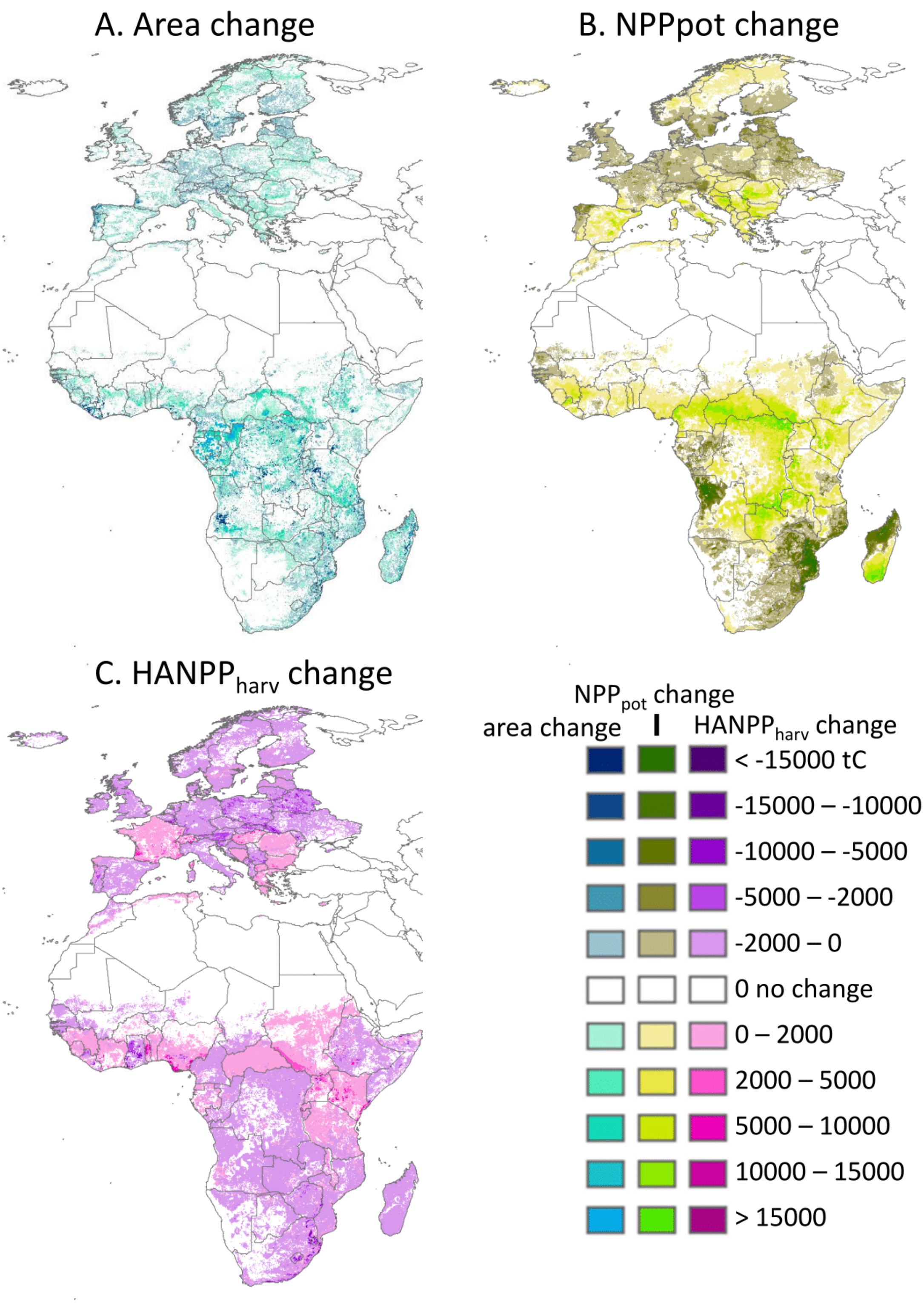


Figure 28: Contribution of area change, NPPpot change and HANPPharv change to change of NPPeco on forest land between 2000 and 2013 in tC.

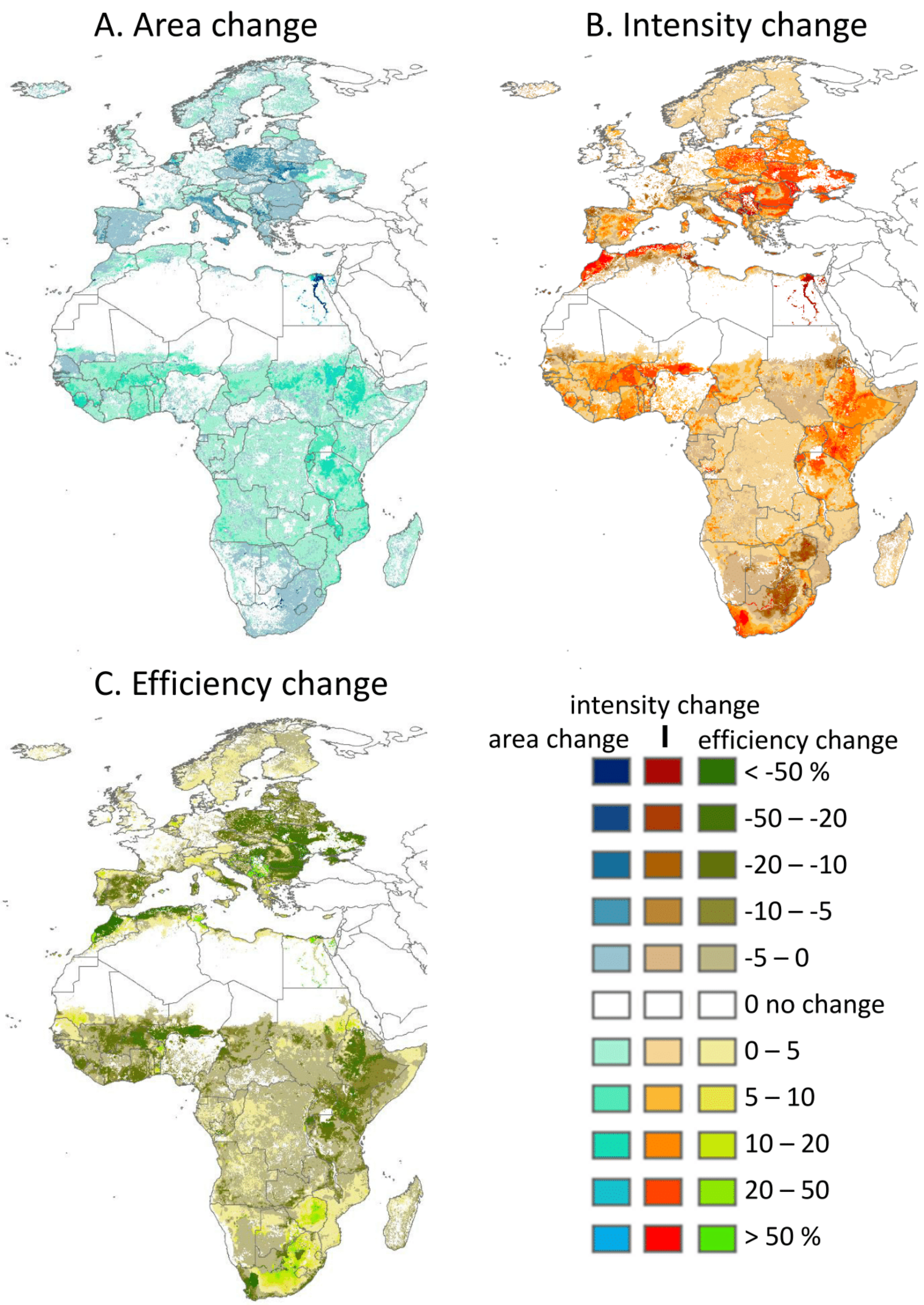


Figure 29: Contribution of area change, intensity change and efficiency change to change of HANPP on all land use types combined between 2000 and 2013 in %.

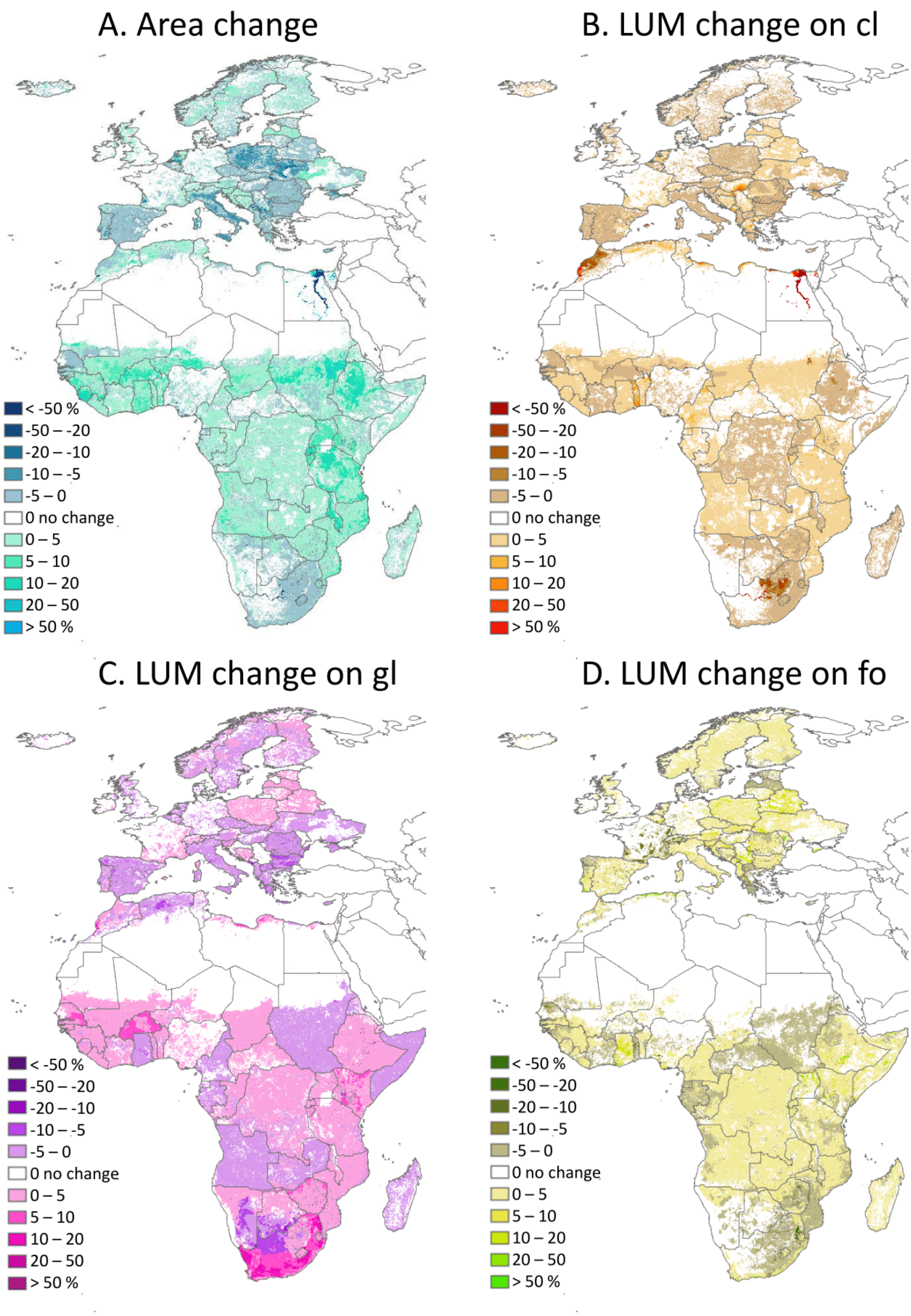


Figure 30: Contribution of area change and land use management (LUM) change on cropland, grazing land and forest land to change of HANPP on all land use types combined between 2000 and 2013 in %.

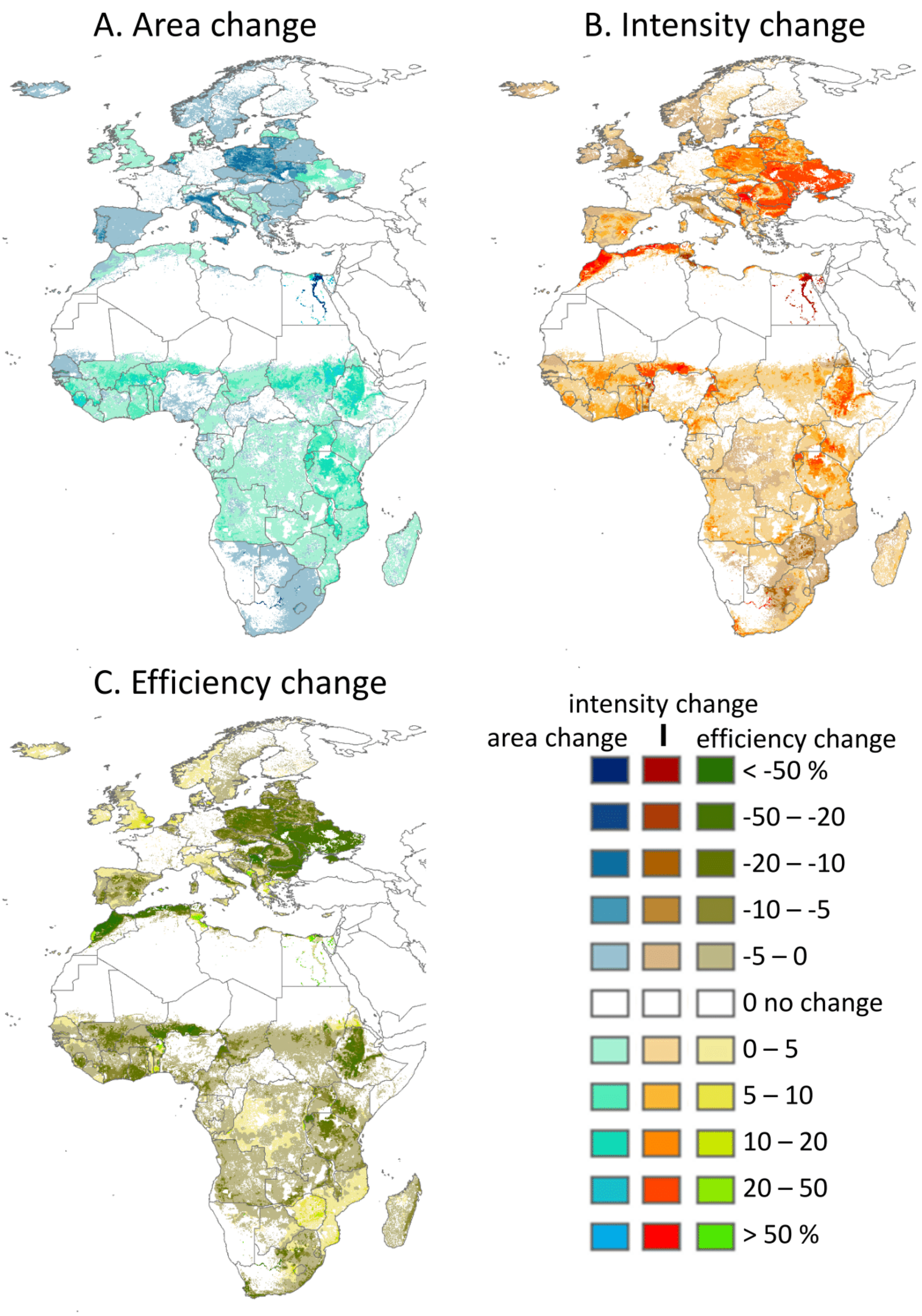


Figure 31: Contribution of area change, intensity change and efficiency change to change of HANPP on cropland between 2000 and 2013 in %.

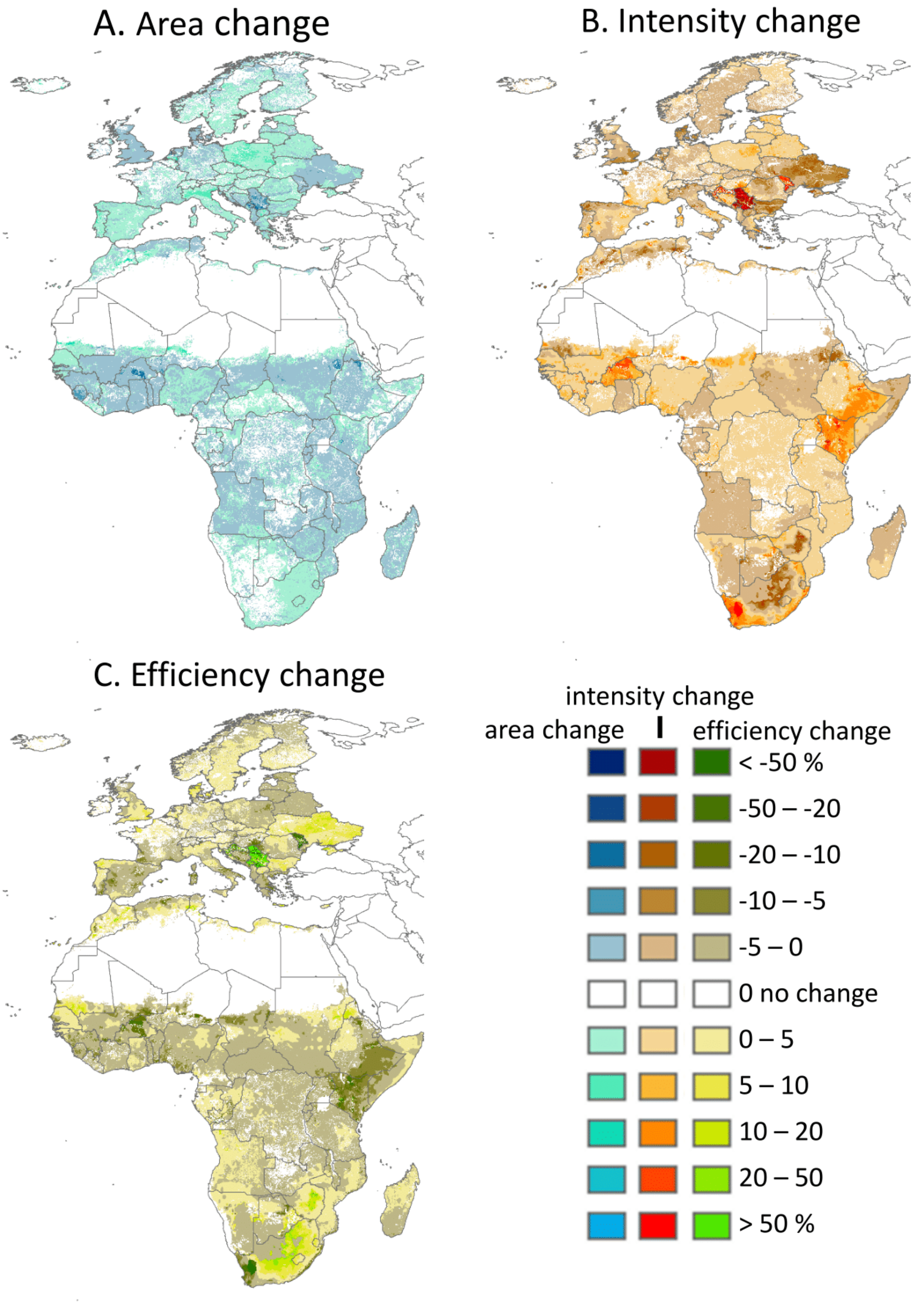


Figure 32: Contribution of area change, intensity change and efficiency change to change of HANPP on grazing land between 2000 and 2013 in %.

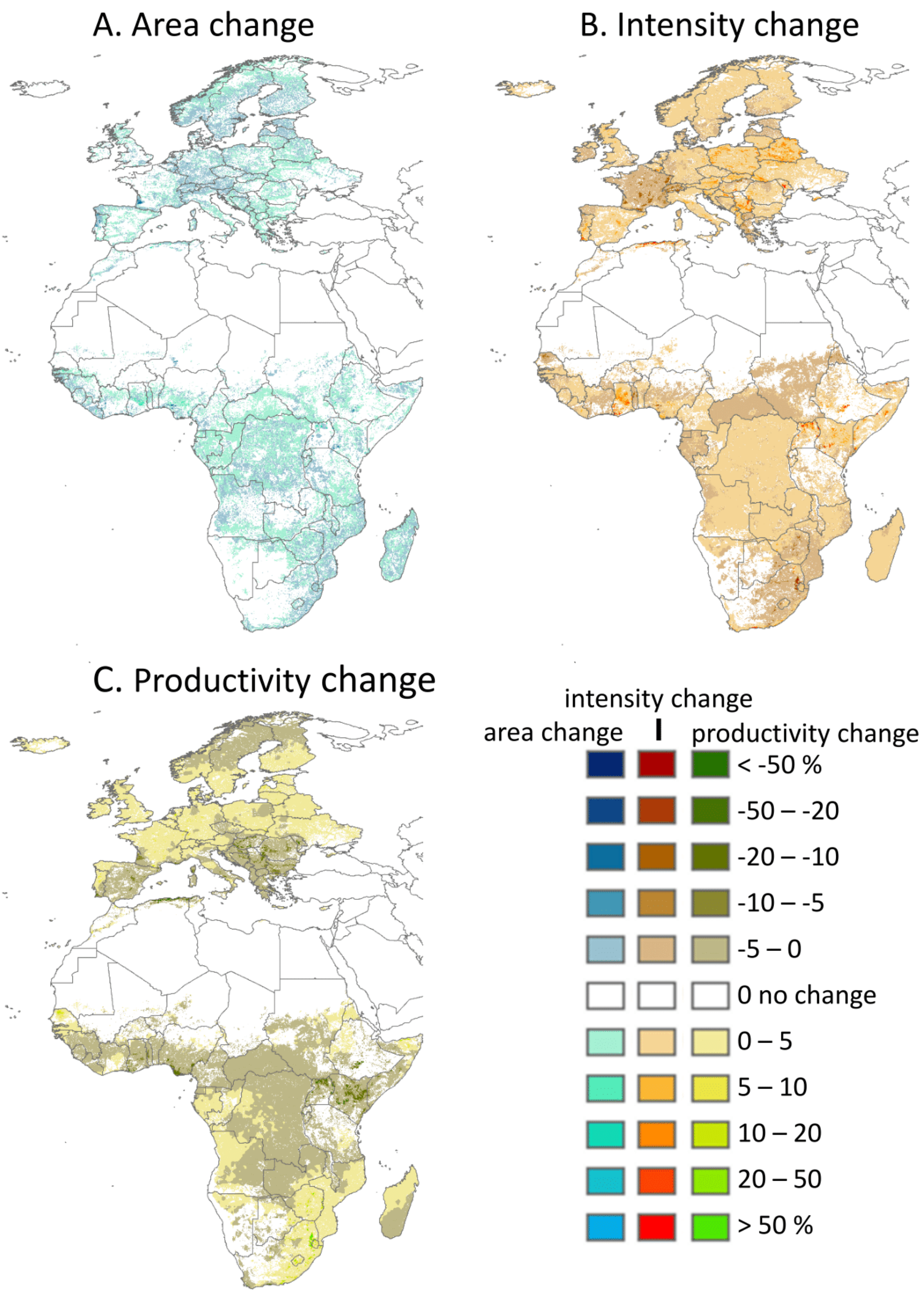


Figure 33: Contribution of area change, intensity change and productivity change to change of HANPP on forest land between 2000 and 2013 in %.