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LETTER

Mapping and analysing cropland use intensity from a NPP perspective

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Abstract

Meeting expected surges in global biomass demand while protecting pristine ecosystems likely requires intensification of current croplands. Yet many uncertainties relate to the potentials for cropland intensification, mainly because conceptualizing and measuring land use intensity is intricate, particularly at the global scale. We present a spatially explicit analysis of global cropland use intensity, following an ecological energy flow perspective. We analyze (a) changes of net primary production (NPP) from the potential system (i.e. assuming undisturbed vegetation) to croplands around 2000 and relate these changes to (b) inputs of (N) fertilizer and irrigation and (c) to biomass outputs, allowing for a three dimensional focus on intensification. Globally the actual NPP of croplands, expressed as per cent of their potential NPP ($NPP_{act\%}$), amounts to 77%. A mix of socio-economic and natural factors explains the high spatial variation which ranges from 22.6% to 416.0% within the inner 95 percentiles. $NPP_{act\%}$ is well below NPP_{pot} in many developing, (Sub-) Tropical regions, while it massively surpasses NPP_{pot} on irrigated drylands and in many industrialized temperate regions. The interrelations of NPP losses (i.e. the difference between NPP_{act} and NPP_{pot}), agricultural inputs and biomass harvest differ substantially between biogeographical regions. Maintaining NPP_{pot} was particularly N-intensive in forest biomes, as compared to cropland in natural grassland biomes. However, much higher levels of biomass harvest occur in forest biomes. We show that fertilization loads correlate with $NPP_{act\%}$ linearly, but the relation gets increasingly blurred beyond a level of 125 kgN ha^{-1}. Thus, large potentials exist to improve N-efficiency at the global scale, as only 10% of global croplands are above this level. Reallocating surplus N could substantially reduce NPP losses by up to 80% below current levels and at the same time increase biomass harvest by almost 30%. However, we also show that eradicating NPP losses globally might not be feasible due to the high input costs and associated sustainability implications. Our analysis emphasizes the necessity to avoid mono-dimensional perspectives with respect to research on sustainable intensification pathways and the potential of integrated socio-ecological approaches for consistently contrasting environmental trade-offs and societal benefits of land use intensification.

1. Introduction

One of the greatest challenges humankind faces in the coming decades is to supply sufficient amounts of food, feed, fiber and energy to a growing and prospering world population while preserving environmental integrity [1–3]. Deforestation is a virulent threat to global sustainability [4], largely driven by cropland expansion, particularly in developing countries [5]. From a production-based perspective minimizing deforestation while increasing biomass outputs will require intensification of current agricultural areas [6, 7].

In the past, intensification of croplands has turned out to be a double edged sword. It has enabled a decoupling of population growth from agricultural expansion [8] and has dampened the growth of net primary production (NPP) appropriated by society [9, 10], but it has also contributed to pressures on global ecosystems and to climate change due to surging inputs of fertilizers and irrigation [11–14]. In the light of this dilemma, exploring ways of 'sustainable intensification', the basis of which is, achieving production increases under environmentally and socially sound conditions [15], is regarded as a key option to reconcile objectives of food security, food sovereignty and environmental protection [3, 6, 15, 16].

Yet we still lack important knowledge on the potentials, environmental costs and socio-ecological benefits of land use intensification, particularly at the global level. One of the major problems is that robust indicators for measuring land use intensity are missing [17, 18]. In the past land-use intensity was usually measured either as input intensity, or as output intensity, where both perspectives face particular challenges: (a) defining sound indicators to consistently integrate the various inputs of land-based production, such as fertilization, irrigation, labor and technical energy, so that substitution effects can be grasped, remains intricate [18, 19]. (b) Measuring output intensity intuitively appears more straightforward, because outputs are defined as the yearly amount of produce per land unit. However, results strongly depend on the choice of unit (e.g. monetary versus biophysical), and comparability is limited due to the huge yield variations of different crops (e.g. a factor of more than 10 between wheat and sugar cane; [8]) and between climatic regions [20]. Results also strongly depend on the choice how to account for harvested secondary products, e.g. straw or leaves. Additionally only a few studies integrate effects of land use intensification at the system level as a third dimension (c), such as the often far-reaching impacts on overall land system properties, including biodiversity, the water and nutrient cycles, or carbon fluxes between land and atmosphere. Many land-use dynamics are attached to these system level changes, which have thus been proposed as an integrative components of land use intensity research [17, 18].

In this study, we follow an ecological energy flow perspective on land use intensity based on the analytical framework 'human appropriation of net primary production' (HANPP; [21–23]). We quantify changes of potential (assuming no human intervention) net primary production (NPP; i.e. annual biomass production by vegetation; [24]) due to cropland conversion as a system level metric of land use intensity. NPP changes due to land use resemble the share of trophic energy that is available for other food webs and are thus indicative for biodiversity impacts [25–28]. In line with the definition by Erb *et al* [23] and Haberl *et al* [29] we use the potential NPP (NPP_{pot}) as a reference value for actual NPP (NPP_{act}). NPP_{pot} is only determined by environmental conditions, mainly temperature, precipitation, and, to a lesser degree, soils [24, 30] and is thus independent of technology. This allows us to isolate effects of land management on NPP_{act}. Using a similar concept, Smith *et al* [31] showed that conversion of natural land to cropland resulted in a reduction of 7% of the global potential NPP and that climate, pre-agricultural land-cover type and management system were key determinants for NPP differences.

We here assess the associated biophysical cost-benefit structures of land use by linking the distance between NPP_{act} and NPP_{pot} with nitrogen and irrigation at the cost side, and the amount of biomass harvest at the benefit side. We so analyze the biophysical framework conditions for future sustainable intensification at the level of different ecological biomes. In summary, we aim at answering the following research questions: (1) How large was the distance between actual and potential NPP on global croplands in the year 2000? (2) How high were the costs and benefits of cropland use intensification in different world regions? (3) Which world regions bear the highest potentials for (sustainable) productivity increases from a NPP perspective?

2. Methods

Our analysis is related to the year 2000, for which the currently best available spatially explicit datasets (on a 5 arcminutes resolution) that meet the purpose of this study exist. All input data sets including potential uncertainties are described in more detail in the SOM. For modeling cropland NPP_{act} we used gridded maps of crop yields and crop areas planted from EarthStat [32]. This is the most comprehensive currently available cropland data set, comprising yields and areas of 175 different crops (i.e. compared to 20 crops in the SPAM data set [33]). Crop yields reported in fresh-weights in [32] were converted to NPP values applying the following equation:

$$NPP_x = (Y_x {*}\ DM_x {*}\ CC) / (HI_x {*}\ RS_x). \qquad (1)$$

NPP_x denotes the NPP of crop x, Y_x is the crop yield in tons fresh weight per hectare and year, DM_x and HI_x are the crop specific dry-matter content and harvest index respectively, and RS_x is its root : shoot ratio. CC refers to the Carbon content, which we considered 50% of dry matter biomass [22]. DM, HI and RS-factors were derived from previous studies [9, 34] and were supplemented with factors provided by Monfreda *et al* [32] if necessary. All crop-specific factors are listed in table S1.

NPP_{act} was calculated based on the area weighted mean NPP_x of all crops planted in a grid-cell [32]. NPP losses during plant growth, i.e. through pests and weeding, were accounted for by multiplying NPP_{act} with country-specific factors used in previous studies [9, 34], which distinguish between industrialization

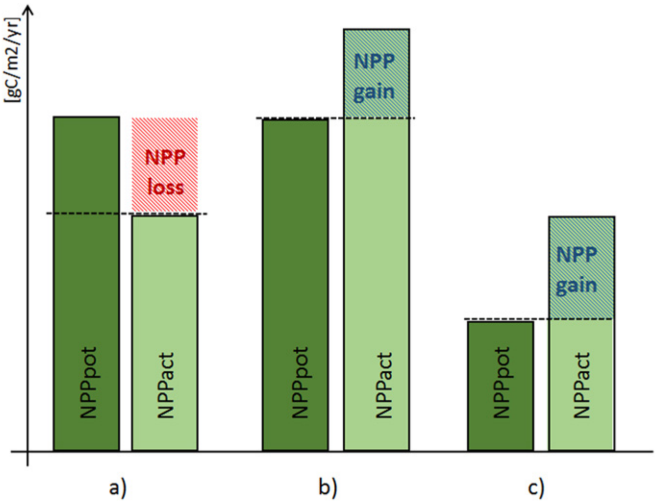


Figure 1. Three hypothetical cases of NPP_{act} in relation to $NPP_{pot;}$ (a) and (b) are two cropland pixels in the same biophysical regions under low (a) and high (b) levels of cropland use intensity; (c) describes a typical irrigated pixel in a dry-land region, where NPP_{pot} is naturally low and NPP_{act} surpassed NPP_{pot}.

levels combined with geographical location. In order to reduce the risk of artefacts in our results, we only considered pixels with a cropland share above 5% per grid cell.

In order to account for higher NPP_{act} in case pixels are cropped more than once a year we multiplied NPP_{act} with a cropping index (CI), following the definition in Siebert *et al* [35], where CI is calculated as the ratio between harvested area (the sum of all cropland areas planted in a grid cell) and cropland extent (here derived from Ramankutty *et al* [36]). Note, that this step has likely produced small artefacts, since information on which crops form the cropping cycle is lacking and the CI was thus applied on the mean area weighted NPP_{act} of all crops in a grid cell.

Next, we calculated the percentage of NPP_{act} to NPP_{pot} ($NPP_{act\%}$) as a metric of system level changes. Potential NPP (NPP_{pot}) was derived from updated model runs of the Lund-Potsdam-Jena Global Dynamic Vegetation Model with an improved representation of hydrology [37, 38]. In order to be consistent with the crop yield data we used the mean NPP_{pot} of the 1997–2003 period.

Figures 1(a)–(c) schematically illustrate the implications of using NPP_{pot} as a reference value for NPP_{act}. (a) and (b) demonstrate two cropland pixels with similar levels of NPP_{pot}. Land management was less intensive in (a) than in (b), resulting in $NPP_{act\%}$ levels below NPP_{pot} (NPP losses) in (a), whereas NPP_{act} was higher than NPP_{pot} in (b), indicating NPP gains. (c) Resembles an irrigated cropland pixel in a dry-land region. Note that NPP_{pot} is substantially lower here, but NPP_{act} surpassed NPP_{pot}, despite being at relatively low levels, i.e. comparable to (a). Hence, while NPP gains in (c) signal positive effects in terms of carbon gains, low NPP_{act} levels signal low productivity per areas and thus low benefits in terms of biomass harvest.

We interpret results on $NPP_{act\%}$ in the background of used extraction per area, i.e. the share of NPP_{act} that enters the socio-economic system. Used biomass is calculated by subtracting pre-harvest losses and unused residues from NPP_{act}. Factors for unused residues were derived from Krausmann *et al* [9, 34] who considers different levels of geographic location and industrialization.

For relating levels of NPP change to input intensity we used a gridded data set of nitrogen (N) consumption on global croplands taken from EarthStat [7], which provides fertilization levels in kg nutrients applied on croplands in a 5 arcminutes resolution. This map represents the improved version of Potter *et al* [39] in terms of spatial accuracy and data quality. It is based on a combination of different statistical data sources (mostly) at the sub-national level and matches the spatial resolution and spatial patterns of EarthStat cropland maps [32, 36]. As a proxy for irrigation input intensity we used a global map on areas equipped with irrigation infrastructure [40].

In order to highlight the influence of biophysical conditions, we interpret land use intensity patterns separately for the main biophysical regions of the world. We used a map on global biomes provided by Olson *et al* [41] and merged several small biomes with larger biomes according to climatic and biophysical similarities and so derived a set of five biomes: (1) Temperate Forest Biome, (2) (Sub-) Tropical Forest Biome, (3) Temperate Grassland Biome, (4) (Sub-) Tropical Grassland Biome, (5) Deserts and Xeric Shrubs Biome. For details on the biome classification refer to figure S5 and table S3.

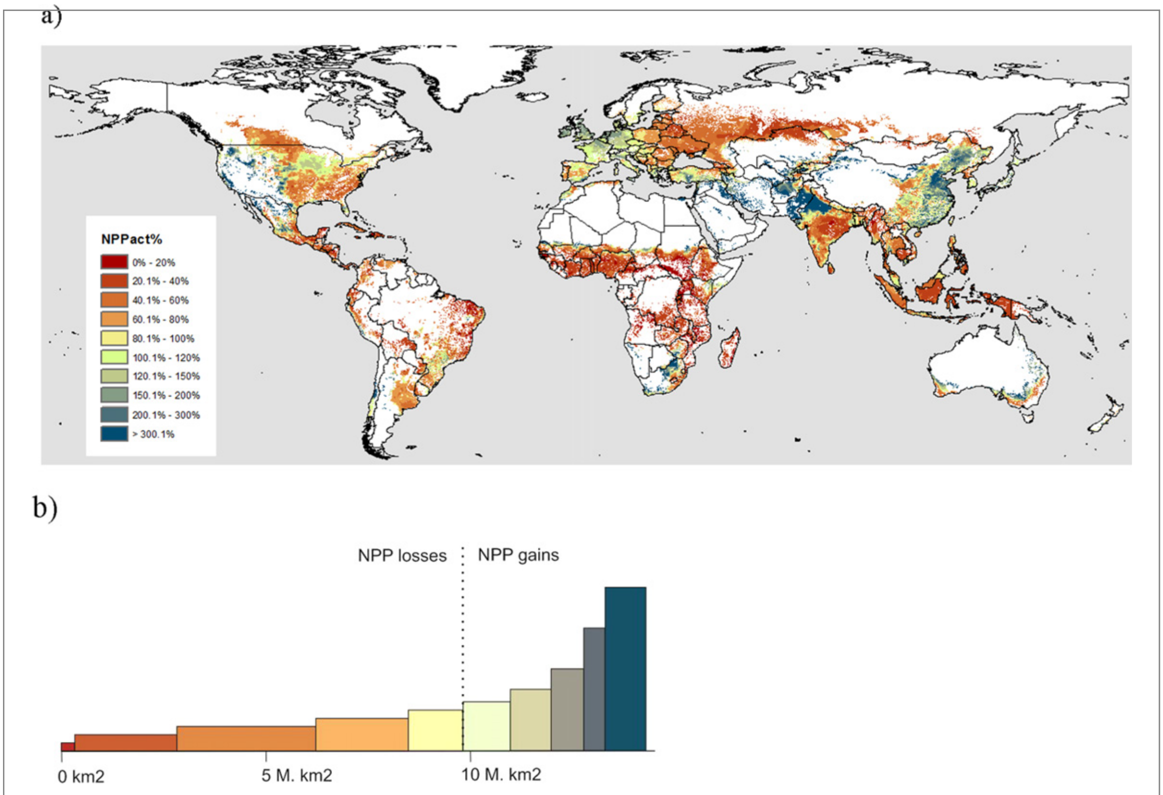


Figure 2. (a) NPP_{act} as percentage of NPP_{pot} (denoted as $NPP_{act\%}$) around 2000; (b) km^2 of cropland per class of $NPP_{act\%}$ indicated by the box-width. Color codes in (a) and (b) match.

Table 1. Combination of inputs and $NPP_{act\%}$ classes. Nitrogen classes are separated according to the input level at the lower, medium and upper 33.3 percentiles of cropland pixels, resulting in the following ranges: 0 to 11.3 kg N per hectare per year (kgN ha^{-1} yr^{-1}) (low input class), 11.3 to 50.9 kgN ha^{-1} yr^{-1} (medium input class) and above 50.9 kgN ha^{-1} yr^{-1} (high input intensity). Irrigation classes are defined based on the share of cropland equipped with irrigation infrastructure per pixels in intervals of 33.3%. $NPP_{act\%}$ is separated into: (1) $NPP_{act} < 80\%$ of NPP_{pot} (significant losses of NPP), 80% to 120% (small changes in NPP, in the following 'constant NPP'), and (3) $NPP_{act} > 120\%$ of NPP_{pot} (significant NPP gains).

$NPP_{act\%}$ **Inputs** ***N, irrigation***	**NPP gain** ($NPP_{act\%} > NPP_{pot}$)	**Constant NPP** ($NPP_{act\%} = NPP_{pot}$)	**NPP loss** ($NPP_{act\%} < NPP_{pot}$)
High	high intensity	low efficiency	lowest efficiency
Medium	high efficiency	intermediate efficiency	low efficiency
Low	highest efficiency	high efficiency	low intensity

3. Results

3.1. Global $NPP_{act\%}$ patterns

In the year 2000, $NPP_{act\%}$ on croplands was on average 23% lower than NPP_{pot}, with large spatial variation (figure 2(a)). On 32% of the global cropland area, NPP_{act} surpassed NPP_{pot} ('cold color' gradient in figures 2(a) and (b), while on the remaining 68% $NPP_{act\%}$ stayed below NPP_{pot} ('warm color' gradient, figures 2(a) and (b). Peak values of $NPP_{act\%}$ can be found in the world's water restricted areas of South-Western Asia, Western US, parts of Southern Africa and Australia; in these regions, $NPP_{act\%}$ exceeds NPP_{pot} by more than a factor ten.

$NPP_{act\%}$ values above 100% are also found in Eastern China, Europe and central US, where they typically reach values between 100% and 200%. Extremely low $NPP_{act\%}$ values are found in tropical regions of central Africa, South-Eastern Asia and parts of Central America, where $NPP_{act\%}$ was below 40% of NPP_{pot}. Around

20% of the global cropland are characterized by such low values. Low $NPP_{act\%}$ was also found over larger regions in Eastern Europe, central Asia and North America, though levels ranged between 40% and 100% in these regions. On 17% of the global cropland area, $NPP_{act\%}$ comes close to NPP_{pot} levels (yellow spectrum in figures 2(a) and (b). These regions are scattered across global croplands and do not appear as strongly delineated regions. Relatively high shares of cropland belong to that class in North America, Southern Europe and Eastern China.

3.2. Relation between $NPP_{act\%}$ and inputs

Table 1 shows the combination of three $NPP_{act\%}$ classes with three classes of N and irrigation input levels, which resulted in nine input-$NPP_{act\%}$ categories. This allows for a systematic analysis of input intensity and NPP changes and thus for detecting patterns of high and low land use intensity (inputs and $NPP_{act\%}$ is both either high or low) and patterns of input-$NPP_{act\%}$ efficiency. Low to medium inputs combined with NPP gains indicate high input-$NPP_{act\%}$ efficiency, whereas high to medium input intensity co-occurring with NPP losses signal low input-$NPP_{act\%}$ efficiency.

Looking at nitrogen inputs, 11% of global croplands show high, and 25% show low N-$NPP_{act\%}$ intensity (figure 3(a)). High intensity pixels are concentrated in the Temperate Forest Biome where they comprise 32% of the croplands, and low intensity pixels are particularly concentrated in the (Sub-) Tropical Grassland Biome, where they comprise half of the croplands.

On all other pixels combinations of N and $NPP_{act\%}$ levels reveal different levels of efficiency. Low and lowest N-$NPP_{act\%}$ efficiency (medium and dark red, dark blue pixels) is particularly virulent in the (Sub-) Tropical Forest Biome, comprising 65% of the pixels there, with a concentration found in South-East Asia and South America, as well as in the Temperate Forest Biome, such as in parts of North America. High N-$NPP_{act\%}$ efficiency (medium and light green, light blue colors) prevails on 14% of global croplands, which are mainly situated in the Desert and Xeric Shrub Biome, as well as in (Sub-) Tropical Grasslands and Temperate Grasslands Biome, comprising 41%, 20% and 14% of the croplands there (figure 3(a)).

The relation between irrigation infrastructure and $NPP_{act\%}$ is less pronounced in most parts of the world (figure 3(b)), so that low irrigation intensity corresponds with high $NPP_{act\%}$ values. An exception are croplands in the Desert and Xeric Shrub Biome in Southern Asia and Westerns US, as well as parts of the Temperate Forest Biome in Eastern China. Here, high irrigation intensity occurs simultaneously with high fertilizer input intensity (dark green colors, figures 3(a) and (b).

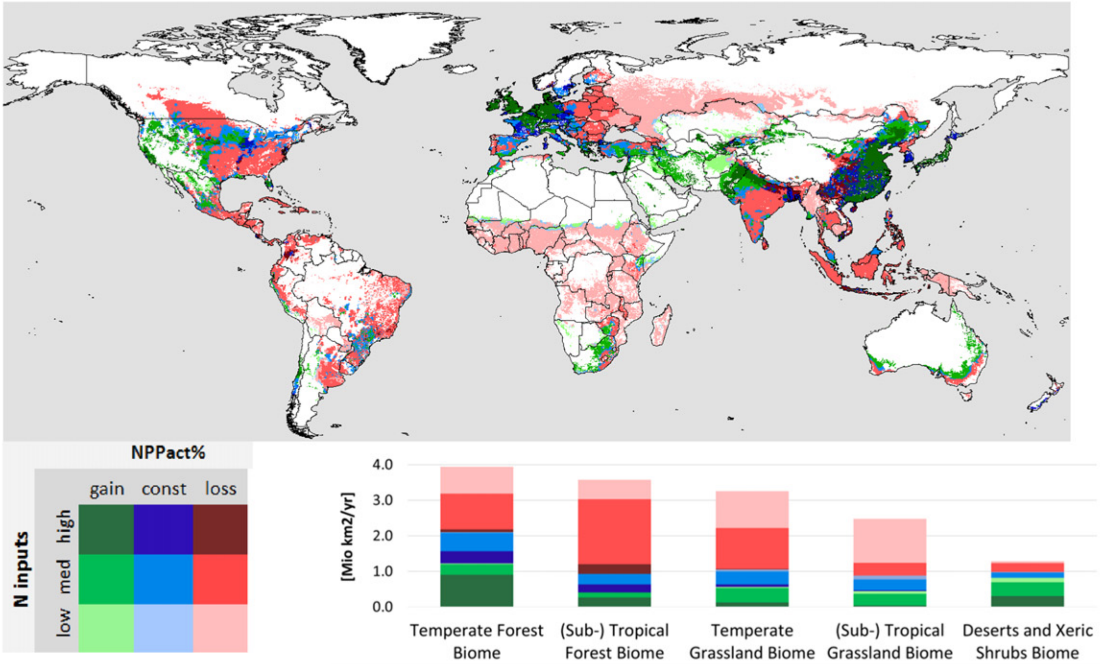
Roughly two Mt Carbon, or 34.4% of global biomass harvest are produced under high N-$NPP_{act\%}$ intensity (figure 4), despite these areas cover only 11% of global croplands. One third of biomass production is associated with NPP losses (red bars, figure 4), while production under high and highest N-$NPP_{act\%}$ efficiency was negligible (light blue and light green bars, figure 3). 8% are produced under low N-$NPP_{act\%}$ intensity, where average outputs per area of 69 gC ha^{-1} yr^{-1} are by far lowest and only amount to 11% of the level under high N-$NPP_{act\%}$ intensity. Interestingly biomass harvest per area was lower under highest N-$NPP_{act\%}$ efficiency (light green bar in figure 4, low N inputs but NPP gains) than under lowest N-$NPP_{act\%}$ efficiency (dark red bar, figure 4), indicating that high biomass harvest require certain levels on N-inputs, notwithstanding if $NPP_{act\%}$ is lower or higher than NPP_{pot}.

Figure 5 illustrates the trend of $NPP_{act\%}$ along with increasing N. We computed the median $NPP_{act\%}$ (black dot) as well as the second and third quantile (gray shaded area) for individual fertilization classes defined by equal intervals of 2.5 kgN ha^{-1} yr^{-1}. With the exception of the Desert and Xeric Shrub Biome (figure 5(f)), a linear interrelation between $NPP_{act\%}$ and N inputs prevails. This interrelation appears particularly stringent at low to medium N inputs, whereas the interrelations loosens at higher N-levels. This is also indicated by increasing interquartile ranges at high N input levels. At the global aggregate, NPP_{pot} is surpassed by NPP_{act} at a level of 75 kgN ha^{-1} yr^{-1}, on croplands in the (Sub-) Tropical Forest Biome at 164 kgN ha^{-1} yr^{-1} and in the Temperate Forest Biome at 102 kgN ha^{-1} yr^{-1}. On croplands situated in the grassland biomes, $NPP_{act\%}$ surpasses NPP_{pot} at lower levels (69 kgN ha^{-1} yr^{-1} in the (Sub-) Tropical, 68 kgN ha^{-1} yr^{-1} in Temperate Grassland Biome). The interrelation between $NPP_{act\%}$ and irrigation inputs was much weaker, showing lower correlation coefficients and a very high spread of inter-quartile ranges. The results are thus not interpreted further, but can be seen in the figure S4.

4. Discussion

Globally, the conversion of natural ecosystems into croplands has resulted in a NPP reduction of 23% with respect to their natural NPP. On the overwhelming part, i.e. on roughly two thirds of global cropland NPP_{act} was below NPP_{pot}. Hence, croplands on which NPP_{pot} was surpassed by $NPP_{act\%}$ only partly compensated for overall NPP losses. Natural as well as socio-economic factors explain the high heterogeneity of global $NPP_{act\%}$ patterns, which are generally a function of inputs (N and irrigation infrastructure), as well as of natural fertility, as indicated by NPP_{pot}. Integrating biomass outputs with N-$NPP_{act\%}$ efficiency patterns shows that N-$NPP_{act\%}$ efficiency does not match

a) Nitrogen-intensity vs. $NPP_{act\%}$



b) Irrigation-intenstiy vs. $NPP_{act\%}$

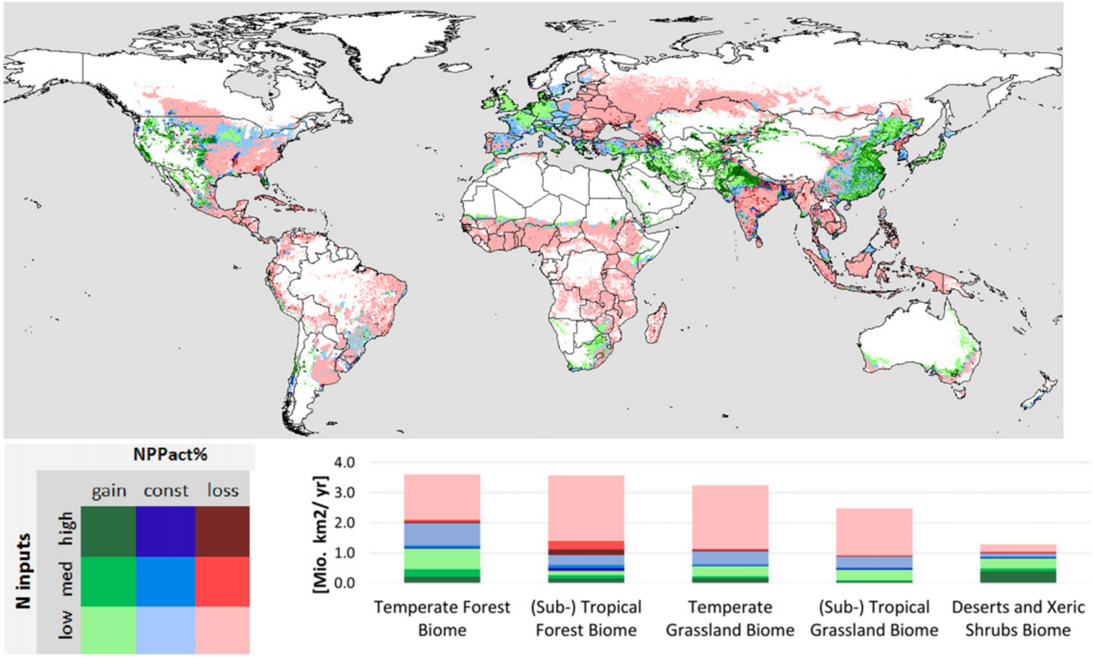


Figure 3. Patterns of input-$NPP_{act\%}$ intensity. (a) Combination of three classes of $NPP_{act\%}$ with (a) three classes of N inputs (33.3 percentile intervals) and (b) three classes of prevalence of irrigation infrastructure; the bar figures show cropland area for each input-$NPP_{act\%}$ class separately for croplands in the five biomes.

with high levels of biomass production. Apparently high societal benefits require certain input levels, notwithstanding if $NPP_{act\%}$ was below or higher than NPP_{pot}. Our results highlight that using current N-budgets more efficiently could substantially reduce NPP losses and increase biomass production, but converging to NPP_{pot} globally might not be feasible given the high input costs.

4.1. Relation between $NPP_{act\%}$ and inputs

Several mechanisms could account for this overall reduction in NPP. First, cropland agriculture favors annual plants while the potential vegetation often consists of perennial plants. The growing periods of croplands are often short and sometimes they are also kept short after harvest in order to prevent the emergence of pests. Furthermore, cropland is often

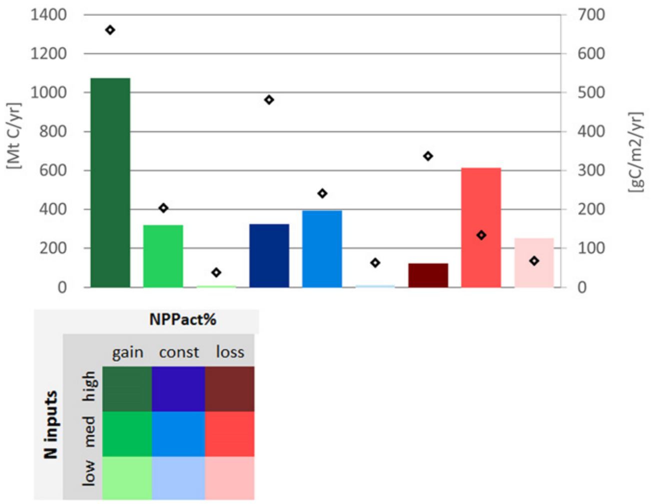


Figure 4. Biomass harvest in a break-down to N-input vs. $NPP_{act\%}$ classes. The secondary axis shows biomass harvest per area (diamonds).

characterized by smaller leaf area indices (a measure of the amount of photosynthetic active tissue) than the potential vegetation, which often consists of forests [42]. Lastly, cropland harvest withdraws nutrients from the ecosystems which affects plant growth if not compensated by crop rotation (fallows) or fertilization.

Compensating for the abovementioned effects in order to converge or surpass to NPP_{pot} requires agricultural inputs, mainly fertilization and/or irrigation. Our results show that $NPP_{act\%}$ is much less correlated with irrigation (figures 3(a), (b); 5 and S4), than with fertilization, indicating that in most world regions nutrients are the key limiting factors. This is not surprising given that much of the world's croplands are in regions with sufficient rainfall. The only exceptions are croplands in the Desert and Xeric Shrubs Biome, where 40% of the croplands are irrigated (not shown here) and fertilization rates are above world average, indicating intensive crop management (table S4).

A mix of of socio-economic and biophysical factors likely explains the remarkable differences of N-$NPP_{act\%}$ efficiency patterns between the world's biomes (figures 3(a) and (b)). High cropland-use intensity was particularly concentrated in the Temperate Forest Biome (figure 2(a)), which covers a large fraction of the industrialized world in Europe, North America as well as Eastern China, where cropland management is typically intensive, revealing high levels of mechanization and agricultural inputs [6]. In contrast, croplands in the (Sub-) Tropical Grasslands Biome stand out with a particularly high share of low-intensity croplands, which are concentrated in developing regions of Sub-Saharan Africa and South America. Fertilization levels are lowest here, i.e. around 21 $\mathrm{kgN\ ha^{-1}\ yr^{-1}}$ on average, explaining the high overall NPP losses of almost 40% of natural NPP (table 2).

However, our results proof that no simple relations between N-levels and $NPP_{act\%}$ exist. 53% of global croplands show either low or high N-$NPP_{act\%}$ efficiency. Low efficiency particularly concern the (Sub-) Tropical Forest Biome, where 62% of global NPP losses occur (table 2). In this region, the extremely high NPP_{pot} (table 2) requires highest N inputs to close the NPP gap (table 2, figure 5(c)). NPP_{pot} thresholds are lower in the Temperate Forest Biome and the Temperate Grassland Biome (table 2). Large regions characterized by low and lowest N-$NPP_{act\%}$ efficiency (high inputs and low $NPP_{act\%}$) located around the US corn-belt and in Eastern China, likely reveal effects of soil degradation and/or salinization due to high input-intensity [43–45], and thus highlight the often far reaching environmental externalities of a high input intensity [46].

Several world regions show that closing the NPP gap does not necessarily need high N-inputs. Water is the key limiting input for the Desert and Xeric Shrubs Biome, where high $NPP_{act\%}$ is always related to high irrigation levels and not necessarily to high N inputs (figures 3(a) and (b)). In Temperate and (Sub-) Tropical Grasslands Biomes high N-$NPP_{act\%}$ efficiency is more common than high land use intensity (figures 3(a) and (b)). Apart from socio-economic constraints that limit high land use intensity *a priori* (table 2, [1, 7, 47]), similarities between the physiology of crop types and the native grassland vegetation that resembles NPP_{pot} might explain N-$NPP_{act\%}$ efficiency. This is particularly true considering similar leaf area indices and carbon allocation strategies [31] between native grasses and cereals (which are, by definition, domesticated grass-types). Examples are the cereal and/or soy growing regions of South Africa, central US, North/Eastern China as well as South/Western Brazil. Hotspots of soy-production generally show low to moderate levels of N-inputs due to

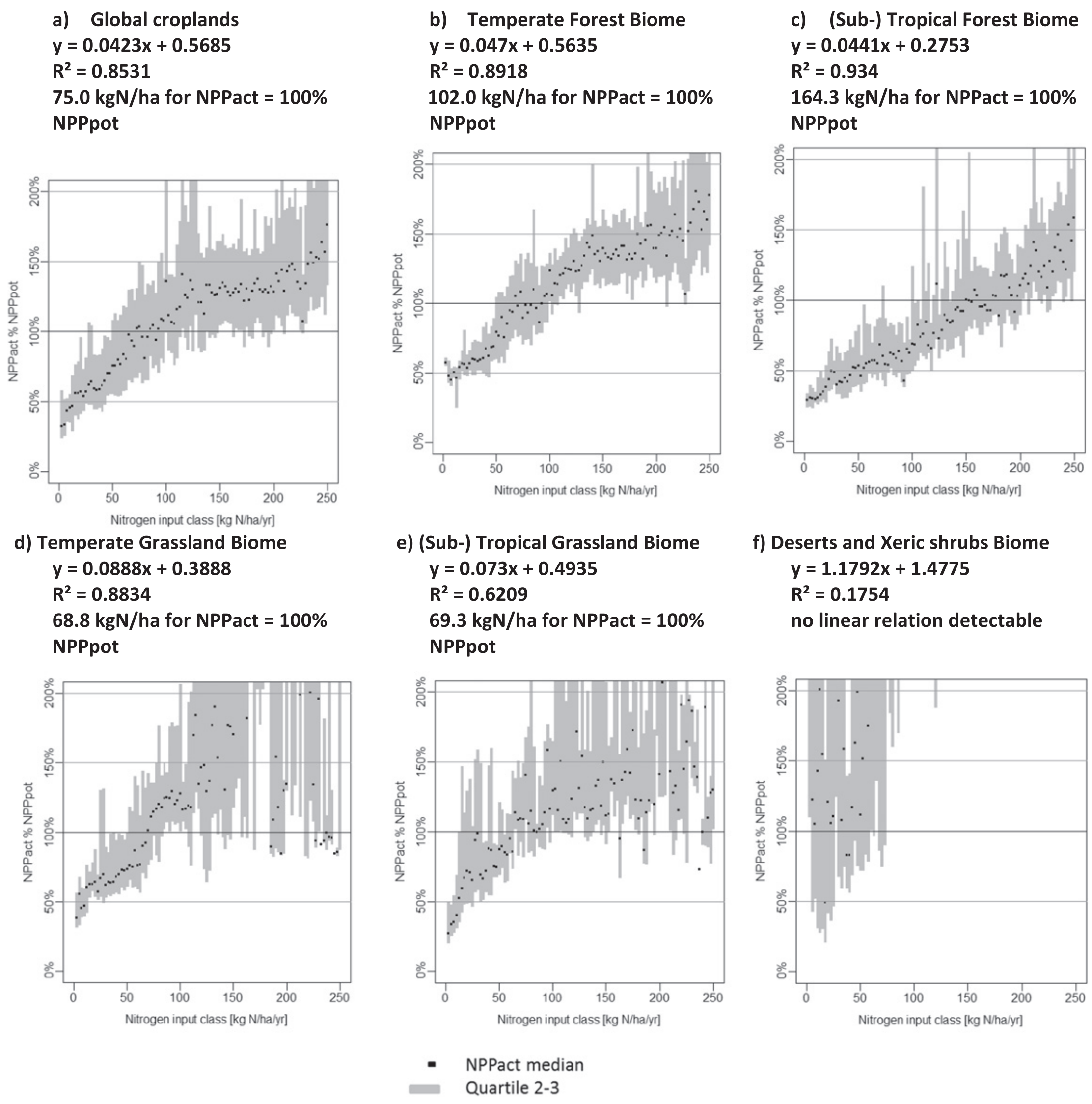


Figure 5. Relations between the level of N inputs (shown as classes in intervals of 2.5 kgN ha^{-1} yr^{-1}) and NPP$_{act\%}$, shown separately for the global average (a) and croplands situated in the five biomes (b)–(f). Graphs are box plots of the 2nd and 3rd quartile (gray shaded area) per N use class, the black dots indicate the median of NPP$_{act\%}$. R^2 values refer to the correlation between the NPP$_{act}$ median of each group and N inputs according to the linear model.

biological N-fixation and thus require lower inputs of other N-sources [48].

4.2. Intensification potentials and their costs

Societies strive to maximize their output in terms of biomass harvest, which is why the integration of biomass benefits into the picture of N-NPP$_{act\%}$ efficiency is crucial. Our split into different combinations of N and NPP$_{act\%}$ enables us to systematically assess obtained biomass per N-NPP$_{act\%}$ efficiency class (figure 4). High levels of biomass harvest require certain levels of N-inputs, where highest biomass returns occur in the high N-NPP$_{act\%}$ intensity class (figure 4, dark green bar). Biomass harvest per unit area decreases along with decreasing N-NPP$_{act\%}$ intensity. Croplands with high N-NPP$_{act\%}$ efficiency (= low N inputs but high NPP$_{act\%}$) contribute relatively little to global biomass harvest, both in quantity and as harvest per area. Thus, highest potentials to increase biomass harvest can be expected from the one quarter of global croplands under low N-NPP$_{act\%}$ intensity (figure 4, light red bar). However, additional N-inputs in this class are mandatory according to our results.

Using current N-budged more wisely, i.e. through a more balanced distribution of N across global croplands could substantially contribute to sustainable intensification of areas that currently face N-deficits (table 2). Around 10% of global croplands are characterized by N-levels above 125 kg ha^{-1} yr^{-1}. At this level no clear relationship exists between increased N input and further increases in NPP$_{act\%}$ (figure 5(a). Capping N-use at 125 kg ha^{-1} yr^{-1} globally would free up 31.4 MtN. More than 60% of this surplus-N would stem from the Temperate Forest Biome (table 2), i.e.

Table 2. NPP change and biomass production under different scenarios of fertilizer use. Results are shown separately for all biomes except for deserts, where the relation between N and $NPP_{act\%}$ was not significant. Scenario 1 describes the situation if surplus nitrogen (above 125 kg ha^{-1} yr^{-1}) is reallocated within each biome to areas below 125 kgN ha^{-1} yr^{-1}. Scenario 2 is the situation when global surplus fertilizer is redistributed to areas where lowest N levels are required to converge NPP_{act} to NPP_{pot}. Scenario 3 describes the situation if NPP_{act} converges to NPP_{pot} globally. Scenario 4 uses current biomass harvest amounts and recalculates required N if N is used more efficiently.

Scenario	Indicator	Unit	Temperate Forest Biome	(Sub-) Tropical Forest Biome	Temperate Grassland Biome	(Sub-) Tropical Grassland Biome	Global croplands
Current	Cropland	Mkm2	3.9	3.6	3.2	2.5	**13.2**
	Cropland with surplus	Mkm2	0.9	0.4	0.0	0.0	**1.4**
	N use	MtN yr^{-1}	32.9	21.8	11.5	5.3	**71.5**
	Surplus N	MtN yr^{-1}	19.7	8.1	0.3	0.4	**31.4**
	Biomass harvest	MtC yr^{-1}	1 117.9	874.1	550.0	300.1	**2842.2**
	NPP losses	MtC yr^{-1}	−23.5	1 107.2	367.7	542.1	**1993.4**
Scenario 1: N-Redistribution within region	Biomass harvest	MtC yr^{-1}	1 647.7	1 107.8	557.4	307.6	**3620.6**
	Biomass increase	%	+47%	+27%	+1%	+3%	**+27%**
	NPP loss[a]	MtC yr^{-1}	−947.1	667.9	351.9	524.9	**597.6**
	NPP loss reduction	%	−3922%	−40%	−4%	−3%	**−70%**
Scenario 2: Optimal global N-allocation	Biomass harvest	MtC yr^{-1}	1 117.9	874.1	1 384.8	300.1	**3677.0**
	Biomass increase	%	0%	0%	+152%	0%	**29%**
	NPP loss	MtC yr^{-1}	−23.5	1 107.2	−1 407.3	542.1	**218.4**
	NPP loss reduction	%	0%	0%	−483%	0%	**−89%**
Scenario 3: NPP_{act} to NPP_{pot} contract & convergence	Biomass harvest	MtC yr^{-1}	1 497.6	2 432.6	1 018.5	689.3	**5637.9**
	Biomass increase	%	34%	178%	85%	130%	**98%**
	N use	MtN yr^{-1}	36.2	59.2	22.0	17.3	**134.7**
	N use increase	%	+10%	+172%	+91%	+227%	**+88%**
Scenario 4: N efficiency constant biomass harvest	Biomass increase	%	0%	0%	0%	0%	**0%**
	N use	MtN yr^{-1}	25.4	18.8	11.4	5.2	**60.8**
	N use reduction	%	−23%	−14%	−1%	−2%	**−15%**

[a] Negative values indicate NPP gains ($NPP_{act\%}$ was higher than NPP_{pot}).

the biome, where most highly industrialized countries are situated. Several reallocation scenarios are thinkable. Within-biome reallocation of surplus N (table 2, Scenario 1) could potentially increase biomass harvest by +27% (applying the linear model for biomass harvest and N-use, refer to the SI), while NPP losses could be reduced by −70%. However, this would have little effect on harvest increases in biomes where surplus-N is low (e.g., the two grassland biomes). Benefits are higher and potentially grant harvest increases by +29% and NPP loss reductions by −89%, if surplus-N is first allocated to biomes where the lowest N inputs are needed for $NPP_{act\%}$ to converge to NPP_{pot} (table 2, Scenario 2; figure 5). Such top-down optimization scenarios would deeply impact on global trade relations between countries and regions. However, global trade has rather accelerated, than leveled off N-imbalances in the past [49].

Converging $NPP_{act\%}$ to NPP_{pot} globally (and contracting to NPP_{pot} where $NPP_{act\%}$ was already higher) bears the highest potentials to raise biomass harvest, i.e. an expected increase by 98% globally (table 2, Scenario 3). However, with current production methods, this scenario implies a massive increase in N-use (by 88% globally), where (Sub-) Tropical Forests would need another 59 MtN yr^{-1} (a growth by 175%). This would likely exceed sustainability thresholds. In contrast, current biomass harvest could be achieved under 15% lower levels of N-use (table 2, Scenario 4), with highest reduction potentials found in the Temperate Forest Biome and in the (Sub-) Tropical Forest Biome (potential N reduction by −25% and −14% over current levels).

Halting, or reducing NPP losses from cropland conversion, while warranting food security and natural protection is a major challenge for the 21st century. Although our results highlight the potentials of a more balanced distribution of global N to reduce NPP losses and raise biomass harvest, sound global policies are the prerequisites for easing inequities of input-use between different world regions. This renders the above scenario difficult to be realized. As no simple solutions exist for an increasingly globalized problem, there is a strong mandate to focus also on consumption-side measures, including a reduction of food waste and a reduction of cropland used for animal and biofuel feedstocks [50].

4.3. Limitations of the analysis

Many uncertainties mainly relating to the used data have to be kept in mind when interpreting our results. The robustness of spatially explicit cropland data is still unsatisfactory [51]. A recent comparison between the M3 cropland map [36], which was used for calibration by Monfreda *et al* [52] and a newly derived cropland map [53] revealed particularly high uncertainty of spatial patterns in Central, Southern and Northern Africa, as well as in Brazil. Since crop yield/area maps used here were calibrated with agricultural inventory data, potential errors/uncertainties in the primary statistics are also inherited in the crop maps. We did not include fallow land in our calculation of NPP_{act} on current croplands, which might have led to underestimations of NPP_{act} in some world regions. These effects, however, are likely counterbalanced by possible overestimations of NPP_{act} on multi-cropping areas. Also, N application refers to mineral N only and does not include N from manure applied [7].

Another major source of uncertainty relates to the spatial resolution of the underlying data sets, which is too coarse to adequately map small scale agriculture, particularly in complex mosaic landscapes. Thenkabail *et al* [54] showed that differences in spatial resolution of cropland maps could partly explain the high disagreement of cropland patterns between different studies. For more details on potential uncertainties related to the input data sets refer to the SOM (chapter S1.1).

In terms of actual NPP, Ito *et al* [55], report an uncertainty level of ±15% globally. A comparison with Smith *et al* [31] shows that different NPP data sources indeed affect the results. Using satellite derived data for NPP of the natural vegetation (analogous to NPP_{pot}) they calculated a 40% higher absolute amount of carbon losses, which owes to greatly differing estimates of NPP_{pot} (2.9 GtC yr^{-1} versus 1.8 GtC yr^{-1} in our study). In consequence, the share of areas experiencing NPP losses is larger (87% versus 77% of global croplands in our study). A recent study on wheat yield projections [56] revealed that under conventional management climate change, will drastically reduce yields in the coming decades. Hence, potential harvest increases calculated in this study would likely be lower under consideration of climate change impacts.

Our results support findings of previous studies, which found highest yield gaps prevailing in Sub-Saharan Africa and Eastern Europe [7, 56], where reallocating global N could raise biomass production by 30% [57]. Interestingly, our results differed in other world regions. Most prominently Mueller *et al* [7] found low yield gaps in most parts of Northern American croplands, where our results indicate NPP gaps, of up to 40% of NPP_{pot}. Hence, while physical yields might have already approached yield ceilings here, related NPP losses indicate simultaneous environmental externalities, such as biodiversity losses [58] or changes in the water cycle [21].

5. Conclusion

Feeding a world of nine billion people will require sound evaluations of the costs and benefits of both, increasing global land use intensity and expanding global croplands. The NPP perspective on global cropland use reveals that large efficiency gains can be expected from a better (spatial) allocation of agricultural inputs. In particular, large regions are characterized by low land use intensity and low efficiencies, warranting further scrutiny. Input costs required to converge to natural NPP differ substantially between biophysical regions. But high N requirements particularly in the (Sub) Tropical Forest Biome render it difficult and likely cost-inefficient to converge to natural NPP globally. Assessing the impacts of re-allocating or, even, increasing N fertilizer consumption and irrigation, was beyond the scope of this paper. Such assessments are, however, indispensable if viable strategies of sustainable intensification are to be defined.

Our findings underline the complexity of measuring land use intensity as well as the efficiency of land use. Many aspects related to costs, benefits and potentials of cropland use intensity remain unknown. The further development of robust, reliable accounting schemes, such as those based on integrated, socio-ecological principles, appear timely, because such schemes provide the basis for any assessment of the potentials, but also the trade-offs and possibly synergies related to future agricultural production, on different locations across the globe.

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