Biogeosciences Discuss., 12, 5435–5475, 2015
www.biogeosciences-discuss.net/12/5435/2015/
doi:10.5194/bgd-12-5435-2015

Biogeosciences
Discussions
Open Access

This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

Mitigation of agriculture emissions in the tropics: comparing forest land-sparing options at the national level

S. Carter[1,3], M. Herold[1], M. C. Rufino[2], K. Neumann[1,4], L. Kooistra[1], and L. Verchot[3]

[1]Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, 6708 PB Wageningen, the Netherlands
[2]Center for International Forestry Research (CIFOR), P.O. Box 30677, 00100 Nairobi, Kenya
[3]Center for International Forestry Research (CIFOR), Jl CIFOR, Bogor 16115, Indonesia
[4]Environmental Research Centre (UFZ), 04318, Leipzig, Germany

Received: 27 February 2015 – Accepted: 12 March 2015 – Published: 10 April 2015

Correspondence to: S. Carter (sarah.carter@wur.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Emissions from agriculture-driven deforestation are of global concern, but forest land-sparing interventions such as agricultural intensification and utilization of available land offer opportunities for mitigation. In many tropical countries, where agriculture is the major driver of deforestation, interventions in the agriculture sector can reduce deforestation emissions as well as reducing emissions in the agriculture sector. Our study uses a novel approach to quantify agriculture-driven deforestation and associated emissions in the tropics. Emissions from agriculture-driven deforestation in the tropics between 2000 and 2010 are 4.3 Gt CO_2 eq yr^{-1} (97 countries). We investigate the national potential to mitigate these emissions through forest land-sparing interventions, which can potentially be implemented under REDD+. We consider intensification, and utilization of available non-forested land as forest land-sparing opportunities since they avoid the expansion of agriculture into forested land. In addition, we assess the potential to reduce agriculture emissions on existing agriculture land, interventions that fall under climate-smart agriculture (CSA). The use of a systematic framework demonstrates the selection of mitigation interventions by considering sequentially the level of emissions, mitigation potential of various interventions, enabling environment and associated risks to livelihoods at the national level. Our results show that considering only countries with high emissions from agriculture-driven deforestation, where there is a potential for forest-sparing interventions, and where there is a good enabling environment (e.g. effective governance or engagement in REDD+), the potential to mitigate is 1.3 Gt CO_2 eq yr^{-1} (20 countries of 78 with sufficient data). For countries where we identify agriculture emissions as priority for mitigation, up to 1 Gt CO_2 eq yr^{-1} could be reduced from the agriculture sector including livestock. Risks to livelihoods from implementing interventions based on national level data, call for detailed investigation at the local level to inform decisions. Three case-studies demonstrate the use of the analytical framework. The inherent link between the agriculture and forestry sectors due to competition for land suggests that these cannot be considered independently.

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This highlights the need to include the forest and the agricultural sector in the decision making process for mitigation interventions at the national level.

1 Introduction

The agriculture and forestry sectors, including deforestation and forest degradation are major contributors of global greenhouse gas (GHG) emissions, accounting for a large proportion (ca. 50 %) of low income countries' total GHG emission budgets (IPCC, 2014). Estimates suggest that emissions from deforestation were $4.9 \pm 0.6\ CO_2\ eq\ yr^{-1}$ in 2010, around 8 % of anthropogenic GHG emissions (Tubiello et al., 2015). According to Hosonuma et al. (2012), in 13 countries agricultural expansion is responsible for 100 % of deforestation. Natural vegetation is at a higher risk than other land cover types, and a quarter is under threat from expansion of agriculture (Creed et al., 2010). Between 1980 and 2000, 83 % of agricultural expansion in the tropics occurred in forested land causing major environmental impacts including loss of carbon stocks and habitats (Gibbs et al., 2010). Agriculture itself has been an increasing source of emissions, growing at around 1 % annually since 1990, to $5.4\ Gt\ CO_2\ eq\ yr^{-1}$ in 2012 (Tubiello et al., 2015).

Land-sparing, or land-saving interventions are supposed to increase the output on agricultural land reducing the need to increase agricultural areas promoting deforestation (Stevenson et al., 2013). Intensification by reducing the gap between potential yield and actual yield (Byerlee et al., 2014; van Ittersum et al., 2013; Neumann et al., 2010; Wilkes et al., 2013) can lead to land sparing. In this study we also consider increasing agricultural production on underutilized land or available non-forested land, for example through rehabilitation of degraded land (DeFries and Rosenzweig, 2010; Wilkes et al., 2013) as a land-sparing intervention. Since we focus on avoiding the expansion of agriculture into forests but not onto other land, this fulfils the aim. These interventions can be potentially included in REDD+ strategies and when implemented with climate smart

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agriculture (CSA) principles can reduce emissions from agriculture as well as avoiding deforestation (FAO, 2013).

The agricultural yield gap can be reduced by interventions into the farming system for example by altering the timing or method of applying agricultural inputs, or increasing cropping frequency. Depending on the introduced change, the intervention will require one or a combination of an increase in labour, capital, technology or a methodological change. Yield gap data provides information on where feasible improvements can lead to increased production (Neumann et al., 2010). The tropics, where yields are typically lower than in temperate regions (West et al., 2010), are often characterized by a rather high yield gap.

Increasing agricultural production on underutilized lands or introducing production on non-forested land provides another opportunity to spare forests. There is generally a consensus that non-utilized, non-forested land is available for agriculture although there is active debate as to the extent (Eitelberg et al., 2015). Available land includes land with potential for intensification, for example degraded grasslands or abandoned cropland.

REDD+ is a results-based financing mechanism which funds activities to reduce emissions from deforestation and forest degradation while promoting forest conservation, sustainable management of forests and enhancing carbon stocks (UNFCCC, 2013). Interventions in the agriculture sector, for example agroforestry, are considered promising options to reduce emissions under REDD+ (Grieg-Gran, 2010), and by 2012, 42 national governments considered agriculture in their REDD+ readiness strategies (Kissinger et al., 2012). However, in many cases countries do not establish REDD+ interventions which address the drivers of deforestation, including agricultural expansion (Salvini et al., 2014). Therefore we believe there is potential to integrate land-sparing interventions into REDD+ efforts to reduce the contribution of agriculture to deforestation.

To evaluate land-sparing interventions, our study systematically compares countries to show which have the largest potential to mitigate GHG emissions from agriculture-

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driven deforestation, and from agriculture (Fig. 1). Firstly we quantify emissions from agriculture-driven deforestation and agriculture in each country. We then pose the question whether closing the yield gap and utilizing available land could be potentially incorporated into the REDD+ context to address these emissions. In addition we assess the potential for reducing emissions directly from existing agricultural land using CSA. We highlight countries which are likely to require increased support to implement mitigation initiatives, by assessing their capacity. Lastly we assess risks to livelihoods from the implementation of interventions by considering food insecurity. Mitigation pathways in three selected countries are explored in depth to illustrate the applications of this framework, and to demonstrate that decisions made using the framework at the global level are relevant for the country level.

2 Data and methodology

Not all tropical non-annex 1 countries (WWF, 2013) or countries who are engaged in REDD+ had data available to assess the mitigation potential (Fig. 1), so this analysis covers only 78 countries which represent 85 % of the forest area in the tropics. However, 97 countries had data available to calculate emissions from agriculture-driven deforestation and of those, two had no data on emissions from agriculture ($n = 95$ for total emissions), so these results are presented (Sect. 3.1).

We developed a framework to assess the current potential of each country to mitigate GHG emissions from agriculture-driven deforestation and agricultural activities (Fig. 2). We look at the potential for mitigation through sparing land by (1) closing the yield gap and (2) by utilising non-forested land suitable for agricultural activities. It is possible that there are synergies which can be exploited by implementing both approaches, however in this study we assume there is potential to mitigate agriculture-driven deforestation when either one of the two approaches is feasible. Where agricultural emissions are largest, the potential to mitigate these emissions is estimated. For countries with a high potential for mitigation, we assess the potential for a mitigation intervention

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to be implemented successfully, by considering constraints to effective implementation (poor governance, lack of engagement in REDD+). Risks to livelihoods as a result of interventions (indicated by food insecurity) are then considered. Data sources were categorized by thresholds at the 1/3rd and 2/3rd percentiles, taking into account all the countries with available data for that input within the tropics for each variable (Table 1).

2.1 Calculation of emissions

The source of emissions is assessed by our framework based on the relative contribution of agricultural emissions and emissions from agriculture-driven deforestation to the sum of the two, which is hereafter referred to as "total emissions" (Table 1).

2.1.1 Area of forest loss

To estimate current deforestation driven by agriculture, we first calculated total deforestation from a combination of historical datasets covering forest changes from 2000–2012 (Table 2). Since we focus on land-use changes (from forest to agriculture), deforestation data based on a forest land-use definition is required. Gross change data are required since, in the cases of China, India and Vietnam for example, large-scale afforestation projects will mean that gains to forest area will underestimate deforestation (FAO, 2010). Since the FRA RSS is sample data which, by definition, does not cover the whole of the tropics, there is no single data source which provides gross forest change with a forest land-use definition. Therefore, where possible (Fig. 3) we use remote sensing based forest-cover change data from Hansen or FRA RSS to derive a ratio of net forest change to forest loss "Net : Loss", and use this factor for estimating gross forest loss from the FAO FRA data (Eq. 1).

$$\text{Gross forest loss} = \text{net forest change}_{\text{FAO FRA}} \cdot \text{Net : Loss}_{\text{Hansen or FRA RSS}} \quad (1)$$

The Net : Loss factor was only calculated where both datasets (FAO FRA and Hansen or FAO FRA and FRA RSS) were in agreement about the direction of net change, i.e.

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both giving negative, or both positive or both no change. Since the number of samples within a country in the FRA RSS varied substantially (from 0 to 930) we used the standard error to determine if the FRA RSS should be used in the analysis. Where the mean was less than the standard error for either the loss or gain in that time period, we did not use the data. We prioritized the Net : Loss ratio for land-use (FRA RSS) over land-cover (Hansen) in Eq. (1).

Data from the FAO FRA are nationally reported and their accuracy is linked to the capacity of the country to provide the information (Romijn et al., 2012). We used this data only when the country was considered able to produce reliable data. Countries whose data we considered reliable were either high income countries (World Bank, 2013), or countries which in 2010 had either an intermediate, high, or very high capacity to measure forest area change (Romijn et al., 2012). Romijn et al. (2012) evaluated the existing monitoring capacities of countries taking into consideration challenges such as the area of forest which the country has to monitor and availability of data.

Where the conditions described above were not met, and Eq. (1) is therefore unsuitable, we selected first the FRA RSS alone to provide the loss, and if this did not meet the error criteria based on the number of samples, we used the Hansen data alone, where it was available. Otherwise we recorded no-data (where only FAO FRA net change is available, no data was also recorded). Data are available for most of the tropics, and the 12 no-data countries (out of 109 countries) account for only 0.02 % of forest area considered in this study. For the majority of the data (countries which hold more than 69 % of forest in the tropics), loss was calculated using FAO FRA in combination with either FRA RSS or Hansen (Fig. 3).

In order to make future projections (since by nature current estimates of deforestation today are based on historic data), a historical baseline period which is sufficiently long to compensate for any anomalous high and low years is required (Santilli et al., 2005). We use 10 years of data, and consider results to be valid for a period of 10 years, which is in line with other studies (e.g. Rideout et al., 2013).

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2.1.2 Area of forest loss due to agriculture

Based on the national total area of deforestation, we calculated the area that was deforested due to agriculture. In this study we use the definition of deforestation drivers used by Hosonuma et al. (2012) and Kissinger et al. (2012). Drivers can be separated into direct and indirect drivers. Since the definition for deforestation considers a change in land use, timber extraction is not considered as a driver, as the forest is expected to regrow. Direct drivers relate to an intended land use (for example, urban expansion, mining, agriculture and infrastructure). Indirectly, international markets and population growth influence the land change. We used national data describing the importance of agriculture as a direct driver of deforestation from Hosonuma et al. (2012). Agriculture includes cropland, pasture, tree plantations, and subsistence agriculture including shifting cultivation (Hosonuma et al., 2012). The authors derived the importance of deforestation drivers from a synthesis of nationally self-reported data, Center for International Forestry Research (CIFOR) country profile reports and other literature, most of them reflecting the timeframe between 2000 and 2010. The relative importance of the drivers mentioned in the reports is reported either as a ratio, ordinal, or nominal scale, and data, depending on the reporting format in the data source. These were scaled between 0 and 1, from minimal to high influence. This indicates the proportion of deforestation which is driven by agriculture (see Hosonuma et al., 2012 for details). We multiplied this "agricultural driver factor" by the area of forest loss "deforestation" to infer the area of loss driven by the agriculture "agriculture-driven deforestation" (Eq. 2).

$$\text{Agriculture driven deforestation} = \text{deforestation} \cdot \text{agricultural driver factor} \tag{2}$$

According to the method used in Harris et al. (2012), we multiplied the area of forest loss by an emissions factor to estimate emissions. We used the average of two above ground biomass (AGB) datasets derived from remote sensing and ground measurements; a tropical dataset (Saatchi et al., 2011) and, a continental dataset (Baccini et al., 2012). Using an average of the two maps is preferred (where there is coverage

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from both datasets), since the accuracy of both approaches is yet to be determined (Zolkos et al., 2013). Where only one map has data, we used the available dataset. After selecting areas with forest cover using the ESA Global Land Cover map of 2010 developed in Climate Change Initiative (CCI) (ESA, 2013), we calculated mean biomass for each country. From AGB, we calculated below ground biomass (BGB) using tree root to shoot ratios equations (Mokany et al., 2006).

2.1.3 Emissions from agriculture

National data from the FAO are available, and to calculate agricultural emissions we summed emissions from agriculture (enteric fermentation, manure management, rice cultivation, synthetic fertilizers, manure applied to soils, manure left on pasture, crop residues, cultivation of organic soils, burning – savanna, burning – crop residues) and agricultural soils (FAO, 2012). We excluded energy use in agriculture. The definition of agriculture includes livestock, and agricultural land is defined as fallow land, temporary crops, temporary meadows for mowing and pasture, permanent crops and permanent meadows and pasture (FAO, 2014a).

2.2 Mitigation potential

We consider two approaches to mitigate agriculture-driven deforestation; closing the yield gap, and utilizing non-forest land for agricultural expansion. Alternatively where the majority of a country's total emissions are from agriculture, we estimate the potential to reduce these emissions through climate smart approaches in the agriculture sector.

2.2.1 Closing the yield gap

Production of maize, wheat and rice provides about two-thirds of all energy in human diets (Cassman, 1999), which makes them good indicators for a national yield gap. First, we calculated the average yield gap of these three cereals for each country based on Neumann et al. (2010). Second, we derived the crop-specific production area per country based on Monfreda et al. (2008). In our study, the yield gap at national level is expressed by the following function (Eq. 3), using yield gaps and production areas of each crop (x).

$$\text{cereal yield gap} = \sum \frac{\text{mean yield gap}_x}{\text{total cereal area}} \cdot \text{cereal area}_x \qquad (3)$$

2.2.2 Non-forested land suitable for agriculture

We used a number of conditions to identify suitable agricultural land, where data are available across the tropics (Table 3, Fig. S1, in the Supplement). These conditions include (1) the biophysical potential; a moderate rainfed yield, low slope, and not classed as barren and (2) the availability of the land; not forested, or used for another purpose (agriculture, urban etc.), or is not used exclusively for agriculture (for example mosaic use with a non-use) and no protected areas. This is likely to be an optimistic estimate since socio-economic and regulatory barriers to land cultivation have not been considered.

2.2.3 Potential for reduction of agricultural emissions

Where the target for emission reductions is in the agriculture sector (Fig. 1), we calculated the emissions $\text{t}\,CO_2\,\text{eq}\,\text{ha}^{-1}$ of agricultural land using national emissions data (Sect. 2.3.1), and agricultural area data (FAO, 2014b). High emissions shows that there are emissions which could potentially be reduced.

2.3 Enabling environment

To represent the enabling environment, we use two indicators: governance and engagement in REDD+. To indicate governance, we summed the following components of a governance index: government effectiveness, regulatory quality, rule of law and control of corruption (World Bank, 2012).

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We produced an index of REDD+ engagement taking into account (1) national engagement in international REDD+ initiatives, (2) sub-national engagement in REDD+ initiatives through project development, and (3) amount of funding acquired. We gave equal weight to the following international programmes: UN-REDD (United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries), FCPF (Forest Carbon Partnership Facility), CIF-FIP (Forest Investment Plan (FIP) within the Climate Investment Funds (CIF)), GEF (The Global Environment Facility), and the Governors' Climate and Forests Task Force. Due to varying levels of participation in some initiatives, weightings were given. We gave countries receiving support from the UN-REDD 1, and partner countries 1/2. There are several steps in the process to gaining an emissions reduction purchase agreement (ERPA) within the FCPF Carbon Fund, so we gave countries who participate (signing a partnership agreement, but yet to submit any documents) 1/3, countries who submitted the RPIN (Readiness Plan Idea Note) 2/3, and countries with a finalized R-PP (Readiness Preparation Proposal), 1. Funding acquisition data were acquired from the Climate Funds Update (www.climatefundsupdate.org), we allocated scores between 0 and 1 depending on the amount secured. The number of REDD+ projects which are occurring in a country are available from the CIFOR database (www.forestclimatechange.org/redd-map/), and we gave scores between 0 and 1 depending on the number of projects (Table S1 in the Supplement). We summed all the scores per country and divided by 7 (the maximum summed score) to create the index with a final score of between 0 and 1.

2.4 Risk assessment

We assessed the risk to livelihoods potentially resulting from the implementation of the mitigation interventions. To identify communities who are at risk (to system changes possibly arising from the interventions), we used a food security index (http://foodsecurityindex.eiu.com/).

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3 Results

3.1 Sources of emissions

In the tropics, a total of 104 260 $km^2 yr^{-1}$ of forest on average was lost between 2000 and 2010/12 (dependent on data input; see Fig. 3) to agriculture (97 countries), which resulted in 4.26 Gt $CO_2 yr^{-1}$ emitted to the atmosphere (Fig. 4.). The largest forest loss due to agriculture occurred in Brazil (29 470 $km^2 yr^{-1}$). On average, countries lost 0.52 % yr^{-1} of their forest to agriculture, with the highest percent loss in Togo (3.71 % yr^{-1}).

The emissions are categorized as follows (Table 1): (1) agriculture-driven deforestation emissions are the main source of the total emissions (> 66 %), (2) agricultural emissions are the main source (> 66 %) and (3) agriculture-driven deforestation and agriculture each contribute 33–66 % to the total emissions. Those countries where emissions from deforestation are highest include those which have high forest losses due to agricultural expansion, e.g., Zimbabwe 1.35 % yr^{-1} (2548 $km^2 yr^{-1}$), and those with a large forest area, e.g., Brazil which loses 0.54 % yr^{-1} (Figs. 4 and 5). Some countries with high agricultural emissions have no deforestation due to agriculture (United Arab Emirates, Djibouti, Eritrea, Mauritania, Niger, Oman, Saudi Arabia). In many cases, countries with a high rate of forest loss also have most emissions from agriculture-driven deforestation, for example Nicaragua which has 0.83 % of its total emissions from agriculture-driven deforestation which is 1.84 % yr^{-1}. Haiti is an exception which has a high forest loss due to agriculture (> 2 % yr^{-1}) but most emissions are from the agricultural sector due to the small forest area remaining (1090 km^2 in 2000, ∼ 4 % of the country area).

3.2 Mitigation potential of agriculture-driven deforestation

In total, 78 countries were classified using the decision tree (Fig. 2), and the main results are presented in Table 4. Out of 44 countries with > 33 % of the total emis-

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sions from agriculture-driven deforestation, 33 also have either have a high yield gap or a large area of available land compared to forest land (Table 4). Available land is highest in South East Asia and West Africa (Fig. 6). The yield gap is highest in East and Central Africa and Central America with the yield gap being already closed in much of Asia and South America (Fig. 6). Of those countries with a high yield gap or large area of available land 20 countries have a good enabling environment in terms of effective governance or engagement in REDD+. These countries have a mitigation potential of 1.32 Gt $CO_2\,yr^{-1}$ from reducing agriculture-driven deforestation. Most countries in Asia and South and Central America have strong enabling environments for interventions, with either effective governance or involvement in REDD+ (Fig. 6). Central Africa has high engagement in REDD+ and some countries in Southern Africa have a high governance scores. Sub-Saharan Africa has the weakest enabling environment for mitigation interventions. Food insecurity indicates a risk to livelihoods when implementing mitigation interventions, and 14 out of the remaining 20 countries have high risks (Table 3). Six priority countries have been identified, which have potential to mitigate agriculture-driven deforestation, and also have a good enabling environment and low risks associated with implementing an intervention: Panama, Paraguay, Ecuador, Mexico, Malaysia and Peru (Table 4).

3.3 Mitigation potential of agricultural emissions

Thirty-eight countries with > 66 % of total emissions from agriculture or who had 33–66 % of total emissions from agriculture and who had no mitigation potential through land-sparing (Fig. 2) were assessed for the potential to mitigate emissions from agriculture. Of those, 12 had a potential to mitigate up to 1 Gt $CO_2\,eq\,yr^{-1}$ of agricultural emissions. However, only two countries had a good enabling environment, and of those only Thailand has low risks associated with the implementation of interventions, so mitigation potential is low.

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3.4 Priority areas for increased support

A number of countries have either little engagement in REDD+ or poor governance which represents a barrier to the successful implementation of interventions. There are 13 countries which have > 33 % of their emissions from agriculture-driven deforestation, have a high potential for mitigation through land-sparing but lack a supportive enabling environment. This accounts for 8 % of emissions from agriculture-driven deforestation. These countries should be assessed for the potential to implement interventions along with capacity building initiatives. Priority candidates for increased support in REDD+ activities are those which have > 66 % of total emissions from agriculture-driven deforestation and which have a high potential for mitigation of agriculture-driven deforestation (Honduras, Liberia, Nicaragua, Venezuela Zambia and Zimbabwe). Where the mitigation potential in the agriculture sector is highest, only Thailand has low risks associated, so implementing intervention in countries with risks associated would require an emphasis on safeguarding.

4 Discussion

4.1 The potential for mitigation of emissions from agriculture-driven deforestation and agriculture

Our results quantify the forest lost each year which is driven by agriculture. Converting forest loss to emissions, and also considering the proportion of emissions which come from agriculture allows mitigation approaches for the main source to be considered. Following this we consider the enabling environment and risks to identify priority countries. This assessment can be used as a starting point for national priority setting and policy processes, although it will not be sufficient to make decisions on local interventions. Countries described as having a low potential for mitigation should also be assessed at the sub-national level for opportunities. Specifically, risks should be as-

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sessed at the local level and even where low risks are identified, activities should be accompanied by safeguards that ensure that the rights and livelihoods of local communities and biodiversity are respected (Peskett and Todd, 2013). REDD+ interventions can potentially bring benefits to communities, but can also bring negative impacts resulting from restrictions on access to forests, changes to permitted land management practices (Peskett and Todd, 2013), or altered agricultural practices (Smith et al., 2013).

We explored three case studies in more detail, providing recommendations based for the mitigation of emissions from both agriculture-driven deforestation and from emissions in existing agricultural land (Table 5). Two cases represent the potential to mitigate deforestation related emissions (Democratic Republic of Congo (DR Congo) and Indonesia), and one highlights the case for targeted interventions within the agricultural sector (Argentina). All countries have emissions $> 1\,\mathrm{Gt\,yr^{-1}}$ (Fig. 2), and have supporting data available to validate the use of the framework for the assessment of the mitigation potential.

4.1.1 Case study: DR Congo

Emissions from agriculture-driven deforestation account for 98 % of the total emissions (emissions from agriculture plus agriculture-driven deforestation). There is a strong consensus that the major direct driver of deforestation in DR Congo is agriculture, and due to increasing populations and weak governance, deforestation rates are likely to increase in the future (Ickowitz et al., 2015). A high mitigation potential exists to reduce agriculture-driven deforestation due to the high yield gap, although available land is rated low (∼ 12 %). Reports suggest that one of the major barriers to implementation of interventions in agriculture is the lack of transport infrastructure and access to markets (Ickowitz et al., 2015). However, engagement in REDD+ is high, suggesting a strong enabling environment for land-use related interventions. There are risks associated with land based activities, since DR Congo is food insecure. Dependence on roots, tubers and plantains is more than 50 % of dietary requirement, and a fall in production over recent years has led to fall in the average caloric intake (Alexandratos and Bru-

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insma, 2012). This together with the country's state of post-conflict recovery suggests that food insecurity will remain in the near future. High risks require a robust safeguard system for local communities, to ensure that food security and income streams are not compromised. Poor governance may complicate implementation, unless concerted efforts are made to support planning and implementation of activities within and between the forestry and agriculture sectors.

4.1.2 Case study: Indonesia

Of the total agriculture and agriculture-driven deforestation emissions, 41 % comes from agricultural emissions in Indonesia. Since Indonesia has available land (55 % of the forested area) and a relatively small yield gap (2.22 t ha^{-1}), the identification of unused land which can be used for growth areas can be explored as a priority. Caution should be taken since the conversion of Indonesia's high carbon peat swamps to can lead to a large flux of emissions – in the case of oil palm this is a change from a net of −1.3 to 30.4 Mg CO_2 eq ha^{-1} yr^{-1} (Hergoualc'h and Verchot, 2013). Amongst all countries included in our analysis Indonesia has the highest engagement in REDD+, and has already implemented national policy interventions designed to protect forests from conversion to agriculture, such as a moratorium on forest conversion (Angelsen et al., 2012). In terms of risks, Indonesia faces some food insecurity, so this should be considered and monitored to ensure that unwanted trade-offs do not result from interventions. Indonesia is a major producer of oil palm and this has led to an expansion of agricultural land (Alexandratos and Bruinsma, 2012). In this case where agriculture and forestry are clearly competing for land, it makes sense to address deforestation and the associated emissions by co-ordinating efforts across sectors.

4.1.3 Case study: Argentina

Although this research concludes that Argentina is not a priority country for interventions since it does not have a high mitigation potential, these findings can still be useful

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to decision making. In Argentina, of the total emissions from agriculture-driven deforestation and agriculture, 73 % comes from agriculture. Argentina has the 8th highest (average 1990–2011) agriculture emissions in the world – largely resulting from livestock keeping (FAO, 2014b), and it is expected that these emissions will continue to rise due to increasing beef demand, so advances in the livestock sector need to be explored for assessing the potential for emissions reductions. In terms of addressing the proportion of emissions from Argentina occurring from agriculture-driven deforestation, there is a large area of available land (our study predicts that this is around 122 % of the forest area) so there is a potential to avoid deforestation. Although our study finds a relatively low yield gap (1.78 $t\,ha^{-1}$) there is still room to narrow, so land-sparing could potentially occur from an intervention targeting the yield gap. Governance is medium in Argentina (−0.35) so interventions are likely to be successful, although some capacity building could be integrated into interventions in the short term, since Argentina's R-PP states that insufficient law enforcement is one of the indirect drivers of deforestation (Kissinger et al., 2012).

4.2 Calculating emissions from deforestation

A number of studies have also calculated emissions from recent deforestation. Achard et al. (2014) uses the FRA RSS sample data (see Sect. 2.1.1) and finds emissions between 2.2 and 4.3 $Gt\,CO_2\,yr^{-1}$ between 2000 and 2010. We find emissions of 5.14 $Gt\,CO_2\,yr^{-1}$ for the tropics, which are 13 % higher than Achard et al. (2014). For 73 tropical countries (excluding the Caribbean), Harris et al. (2012) finds emissions of 1.9–4.73 $Gt\,CO_2\,yr^{-1}$ between 2000 and 2005 from deforestation. Our estimate for the same 73 countries is 4.83 $Gt\,CO_2\,yr^{-1}$, 2 % above the upper limit for Harris et al. (2012). Although our results are higher than these estimates, Harris' estimates are typically 25–50 % of other recent estimates (Harris et al., 2012), which supports our findings. Emissions from deforestation can also be higher, as these studies do not consider losses from peat soils. In terms of the area of deforestation, Harris et al. (2012),

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finds annual forest loss for 73 tropical countries (excluding the Caribbean) of 36 750–143 330 km^2 yr^{-1} (with a median of 85 160). This supports our results for the same countries (we estimate 117 486 km^2 yr^{-1} total forest loss not only driven by agriculture), which lies within the same range. Estimates of deforestation area from Achard et al. (2014) are not easily comparable to estimates based on country reported data (including our study), and disagree with the FAO FRA data partly due to the definition of forests (Achard et al., 2014). The major difference in estimates is from the emissions factors rather than the activity data. Since this paper uses a comparative approach to assess the need for mitigation on a country level, we consider these data still useful for this purpose.

4.3 Predicting agriculture-driven deforestation

Estimates of the mitigation potential of reducing agriculture-driven deforestation are inherently reliant on future estimates of agriculture-driven deforestation. These by nature rely on assumptions about the future, and baseline setting which is one of the challenges of REDD+ (Köthke et al., 2014). Historical deforestation rates are commonly used for setting business-as-usual (BAU) baselines for avoided deforestation (Santilli et al., 2005). We therefore selected this approach for our study, however other approaches can arguably produce better estimates. Adjusting historic baselines based on the forest transition curve (FT) to make predictions can be beneficial since otherwise countries at the early stages of the transition will underestimate future BAU deforestation and countries at later stages of the transition will overestimate BAU (Angelsen, 2008; Köthke et al., 2014). However, future scenarios should also account for global economic forces and government policies which are not accounted for in the FT, and there are a number of countries which do not fit into the typical FT trajectory, for example Thailand (Meyfroidt and Lambin, 2011). Models are often used to estimate deforestation based on relationships between deforestation and variables such as population, and have been used for a number of applications (Kaimowitz and Angelsen, 1998). Global models are useful for estimating deforestation since they account for leakage

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across national borders, and partial equilibrium models (e.g. GLOBIOM) are able to model competition for land, and incorporate data on multiple sectors, e.g. agriculture, forestry and bioenergy. However, there is not always a clear relationship between deforestation and the selected explanatory variables, and some aspects of human behaviour such as social and political changes are impossible to predict, consequently leading to scenarios with high uncertainties (Dalla-Nora et al., 2014; Kaimowitz and Angelsen, 1998). In addition, there is some scepticism on models which are based on assumptions about economic behaviour, and those models which are based on household data are considered most reliable, which are only useful for local level estimates (Kaimowitz and Angelsen, 1998).

4.4 Estimating available land

Land available for agriculture is one of the indicators for the potential to mitigate agricultural expansion into forests, however there are many difficulties in quantifying available land (Lambin et al., 2013). There are several limitations to our the approach including: (1) the rain-fed potential is considered and irrigation can be used to increase productivity, (2) the threshold of 3.5 $t\,ha^{-1}$ can be considered overly conservative, since many areas are cultivated with lower production levels (Droogers et al., 2001), however this is merely the yield potential, and is therefore not comparable with actual yields which may be much lower in many cases, (3) suitability for agriculture is crop specific, so it is possible that there are some crop types which can potentially produce above 3.5 $t\,ha^{-1}$ in the "very-low productivity" areas, (4) it is a static approach which does not take into account expected changes in climate, (5) slopes > 15 % can be cultivated using terracing and erosion is dependent on other factors such as length of slope, soil type and the intended use (FAO, 1976). Regarding the slope, 15 % is commonly used to identify agricultural suitability since this is the threshold where the kinetic energy of the runoff increases and outweighs the kinetic energy of the rainfall thus resulting in erosion (Roos, 1996), so this can be considered a conservative limit. Despite limitations, comparisons with other datasets support the method in this paper. Within the

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tropics we find approximately 8 290 000 km^2 of available land (Fig. S1). This is over 11 % of the total terrestrial area. Other studies also suggest that there are large areas of land available globally and one study which only considers abandoned agricultural land which is suitable for bioenergy production finds that over 3.5 % of the land area is suitable (Campbell et al., 2008). A comparison of three areas for which data are available shows that the areas predicted in this study are within the region of those calculated by Lambin et al. (2013) (Table 6). This is a bottom-up approach estimates the world's potentially available cropland based on a series of constraints and trade-offs which are considered in different scenarios. A global figure of 13 220 000 km^2 was calculated using comparable processes, which is also within the same order of magnitude (Fader et al., 2013).

4.5 The land-sparing hypothesis

Land sparing can only occur if the yield gap is sufficiently closed, and if available land is successfully used. The extent to which the yield gap can be closed in practice depends on location-specific technological, biophysical and other constraints (Duwayri et al., 2000; Neumann et al., 2010). It is widely recognised that technological advances in agriculture which close the yield gap intensify production can reduce the need to expand agricultural production into forests (Borlaug, 2007; Stevenson et al., 2013). Scenarios suggest that a 1 % crop yield increase annually would spare 0.76 billion ha of cropland expansion by 2050 (Sands and Leimbach, 2003). Despite increases in fertilizer use, higher yields avoid emissions, due to a reduced emissions intensity from production (Burney et al., 2010). In order to avoid social and environmental costs, including increased emissions, "climate smart" or "sustainable intensification" principles can be followed (Foley et al., 2011; Garnett, 2012). This theory, however, has been much debated recently, with some research finding that any savings will be offset by changing human diets and increased population (Kastner et al., 2012).

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Few examples are cited in the literature where intensification on or utilization of available land has led to land-sparing (Cohn et al., 2011; Minang et al., 2011; Stevenson et al., 2013), perhaps since few programmes are developed with this aim. However in the case of Brazil, Nationally Appropriate Mitigation Actions (NAMAs) to restore grazing land account for 10–12 % (0.1–0.13 Gt CO_2) of pledged emission reductions for the year 2020 (Cohn et al., 2011).

Even if the yield gap has been closed, and available land utilized, land-sparing must become a reality in order for deforestation to be reduced. Some studies suggest that feedbacks such as increasing land rents from yield improvements will lead to increases in land area dedicated to agriculture (Angelsen, 2010). Intensified production has been found more likely than smallholder production to expand into forests (Gutiérrez-Vélez et al., 2011) and freeing grazing lands can lead to more demand for cropland to supply feed for the livestock (Cattaneo, 2001). However, we consider the level of governance as a criterion in the selection of areas for interventions which will support the integration of policies to limit agricultural expansion such as LSPs (Cohn et al., 2011; Rudel et al., 2009). Governance indicators, such as rule of law and control of corruption (World Bank, 2012) are related to the effective set-up and management of interventions and accompanying policies, and have been used as an indicator of the enabling environment for interventions. The state of Mato Grosso in Brazil is one example where agriculture-driven deforestation has been reduced by the integration of policies including the Soy Bean industry's self-imposed moratorium (2006) on production in deforested areas and pro-active efforts by the local and national governments to control deforestation (DeFries et al., 2013). Nationally Appropriate Mitigation Actions (NAMAs) can also help to achieve targets of agricultural mitigation and also reduce leakage risks and foster wider engagement at the country level, and can be combined within REDD+ mechanisms (Kissinger et al., 2012).

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5 Conclusions

This study gives a comprehensive overview of national emissions and mitigation priorities within the forest and agriculture sectors, which can guide decision making and investments at the international level. Specifically, available data can be used to identify where emissions within the agriculture, forestry and other land use (AFOLU) sector within the IPCC reporting scheme can be best reduced. The inherent link between agriculture and forests highlights need for integrated solutions. Agricultural interventions have been incorporated into REDD+ frameworks in some countries, including Indonesia and Brazil (Kissinger et al., 2012), but generally there is room for improvement to ensure that where agricultural drivers are present, they are addressed with appropriate interventions within the agricultural sector (Salvini et al., 2014).

Our findings show that there is an existing potential to mitigate 4.26 $\mathrm{Gt\,CO_2\,eq\,yr^{-1}}$ from agriculture-driven deforestation. Many countries also have a high potential to implement successful interventions in the agricultural sector, as there is a good enabling environment (effective governance or engagement in REDD+) which will support activities. A potential of 1.32 $\mathrm{Gt\,CO_2\,yr^{-1}}$ can be mitigated in countries, who have > 33 % of their emissions from agriculture-driven deforestation and have a good enabling environment (20 countries), which represents 31 % of the total emissions from agriculture-driven deforestation in the tropics. These countries potentially hold the easiest gains and interventions which seek to spare forest land by decreasing the yield gap, or by expanding agriculture into available non-forest lands and these opportunities should be systematically considered. Some of these countries have risks (e.g. Indonesia and DR Congo) associated with potential activities and this should be considered as part of the decision making process. A number of countries have a high potential but indicators suggest the enabling environment is not strong (e.g. Angola, Honduras) (Table 4). In these cases, longer-term support which also seeks to build governance capabilities can be considered.

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Within the agriculture and forestry sectors in particular, there are potential trade-offs (risks to livelihoods) associated with mitigation interventions. These interventions carry potential social and environmental costs, however using principles of "sustainable intensification" or "climate-smart" agriculture can minimize these costs (Foley et al., 2011; Garnett et al., 2013). Interventions which deliver multiple benefits, in terms of yield increases, mitigation and adaptation components can also offer opportunities to support vulnerable communities where risks such as food insecurity or reliance on agriculture for income are present. There is a need to look beyond the broad interventions which are discussed in this paper, and the growing body of evidence on climate-smart agriculture (FAO, 2013) is providing examples of best practices in specific locations. Further research is also required to consider other risks, for example to biodiversity, which can be impacted by changes to agricultural systems. This systematic framework can be replicated in other scenarios, or at other scales (regional, and local for example) to set priorities for mitigation across sectors in a transparent manner. As new data becomes available, the analysis can be repeated to produce an updated output.

The Supplement related to this article is available online at doi:10.5194/bgd-12-5435-2015-supplement.

Author contributions. M. Herold, L. Verchot and S. Carter designed the study, M. Herold, M. C. Rufino and S. Carter developed the methods, K. Neumann provided data, S. Carter performed the analysis, all authors interpreted the results, S. Carter prepared the manuscript with contributions from all co-authors.

Acknowledgements. This research was generously supported by the contributions of the governments of Australia (Grant Agreement # 46167) and Norway (Grant Agreement #QZA-10/0468) to the Center for International Forestry Research. This work was carried out as part of the Consultative Group on International Agricultural Research programs on Trees, Forests and Agroforestry (FTA) and Climate Change Agriculture and Food Security (CCAFS). The authors thank Valerio Avitabile and John Stuiver for technical support.

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Table 1. Data sources for the identification of target countries for mitigation interventions. Categories are selected by thresholds at the 1/3rd and 2/3rd percentiles.

Decision step		Categories		
Emissions assessment		Agriculture	Deforestation	Both
Total emissions ($t\,CO_2$ eq)	Emissions (CO_2) which come from agriculture-driven deforestation (multiple data sources – see Sect. 2.2) and from agriculture (CH_4, N_2O, CO_2) (Emissions from agriculture 2010 [or most recent data point available] [$t\,CO_2$ eq]* (FAO, 2014b))	> 66 % is emissions from agriculture-driven deforestation	> 66 % is agriculture emissions	33–66 % is emissions from agriculture-driven deforestation and agriculture
Mitigation potential		Low	Medium	High
Yield gap ($t\,ha^{-1}$)	Area weighted yield gap of major grains (Neumann et al., 2010) based on the area under production (Monfreda et al., 2008)	< 2.21	2.21–3.6	> 3.6
Available land (%)	Area of non-forested, non-protected, unused land, with minor slopes < 15 % and a potential for > 3.5 $t\,ha^{-1}$ agricultural production. Expressed as a percentage of forested land (multiple data sources – see Table 2).	< 17	17–44	> 44
Agricultural emissions ($t\,CO_2\,e\,ha^{-1}$)	Emissions (CH_4, N_2O, CO_2) from agriculture 2010 (or most recent data point available) (FAO, 2014b)	< 0.72	0.72–1.68	> 1.68
Enabling environment		Low	Medium	High
Governance	Governance index (government effectiveness, regulatory quality, rule of law and control of corruption) (World Bank, 2012)	< −0.72	−0.72–0.24	> −0.24
REDD+ engagement	Index of engagement in national and sub-national REDD+ initiatives (multiple data sources – see Sect. 2.4)	< 0.14	0.14–0.36	> 0.36
Risk assessment		Low	Medium	High
Food security	Global Food Security Index (http://foodsecurityindex.eiu.com/)	> 51	34–51	< 34

* CO_2 eq – equivalent concentrations of other GHGs in terms of radiative forcing as carbon dioxide.

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Table 2. Description of data sources used to derive deforestation at the national level.

Data	Source	Gross/net	Forest-use/ Forest-cover	Coverage	Resolution	Temporal coverage
FAO FRA	FAO (2010)	Net	Forest-use	Complete	Country	2000–2010
FRA RSS	FAO and JRC (2012)	Gross	Forest-use	Sample	Based on Landsat	2000–2005
Hansen	Hansen et al. (2013)	Gross	Forest-cover	Complete	Based on Landsat	2000–2012

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Table 3. Land available for agriculture – data sources and availability conditions.

Availability factor	Availability condition	Data description
Yield potential for rain-fed agriculture	crop productivity > 3.5 $t\,ha^{-1}$	10 arc minute climate dataset combined with soil water storage map and a dynamic water and crop model (Droogers et al., 2001)
Land is not used and non-forested	Mosaic cropland/tree cover, mosaic herbaceous/tree cover, shrubland and grassland cover classes	300 m resolution land cover map based on a global surface reflectance (SR) composite time series. Data for 2010 available (ESA, 2013)
Suitable topography for agriculture	Slopes < 15 %	30 arc second aggregate based on 90 m resolution digital terrain map from the Shuttle Radar Topographic Mission (SRTM) (Fischer et al., 2008)
Land does not have protected area status	No protected status	Globally spatially referenced database of protected areas (IUCN UNEP-WCMC, 2014)

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Table 4. Countries are categorized into mitigation intervention classes according to the results of the decision making tree (Fig. 1) which identifies target countries for mitigation interventions using thresholds for input data (Table 1). Priority countries (with low risks) for interventions are emboldened (countries for which data are unavailable for the full analysis are not included).

Contribution of emissions to total	Agriculture > 66 %	Agriculture and agricultural driven deforestation emissions 33–66 %		Agricultural driven deforestation > 66 %
Potential for mitigation (sector)	Agriculture	Agriculture	Forest	Forest
High potential and effective governance (or engagement in REDD+ in the case of the agriculture mitigation sector) for mitigation intervention (low risk countries are emboldened)	**Thailand** India		**Panama** **Paraguay** Indonesia Kenya Sri Lanka Madagascar Senegal Uganda Viet Nam	**Ecuador** **Mexico** **Malaysia** **Peru** Côte d'Ivoire Cameroon DR Congo Ghana Guatemala Mozambique Tanzania
High potential but support for governance required (countries are not assessed for risk)	Bangladesh Egypt Gambia Haiti Nepal Pakistan Philippines El Salvador	Dominican Republic Suriname	Angola Benin Ethiopia Guinea Malawi Sierra Leone Togo	Honduras Liberia Nicaragua Venezuela Zambia Zimbabwe
Low potential (countries are not assessed for governance or risk)	Argentina Burundi Burkina Faso Chile China Comoros Cuba Djibouti Algeria Eritrea Jamaica Libya Mali Mauritania Mauritius Niger Nigeria Oman Rwanda Saudi Arabia Somalia Chad Uruguay South Africa	Colombia Guinea-Bissau		Bolivia, Brazil Costa Rica Guyana Cambodia Lao PDR Myanmar

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Table 5. Mitigation potential for DR Congo, Indonesia and Argentina.

	DR Congo	Indonesia	Argentina
Emissions source	Deforestation	Both	Agriculture
Mitigation potential	Reducing deforestation	Reducing deforestation	Agricultural sector
Yield gap	High	Medium	Low
Available land	Low	High	High
Agricultural emissions	Low	High	Low
Enabling environment	Yes	Yes	No
Governance	Low	Medium	Medium
REDD+ engagement	High	High	High
Risk factor	Yes	Yes	No
Food insecurity	High	Medium	Low

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Table 6. Available land area (in '000 km^2) for three regions

Source	Availability definition	DR	Indonesia Congo	Brazilian and Bolivian Amazon*
This study	All available land	195	547	383
Lambin et al. (2013)	Land cover classes with potential for agricultural expansion (1)	854	638	385
	Areas excluding those with major constraints (2)	240	75	124
	Areas excluding those with trade-offs (3)	140	50	74

* The Brazilian and Bolivian Amazon region consists of Bolivia, and 5 states in Brazil; Maranhão, Pará, Mato Grosso, Rondônia, and Acre (the Lambin et al. (2013) area is slightly smaller, as it only considers Pará south of the Amazon River, which is the "Amazon arc of deforestation").

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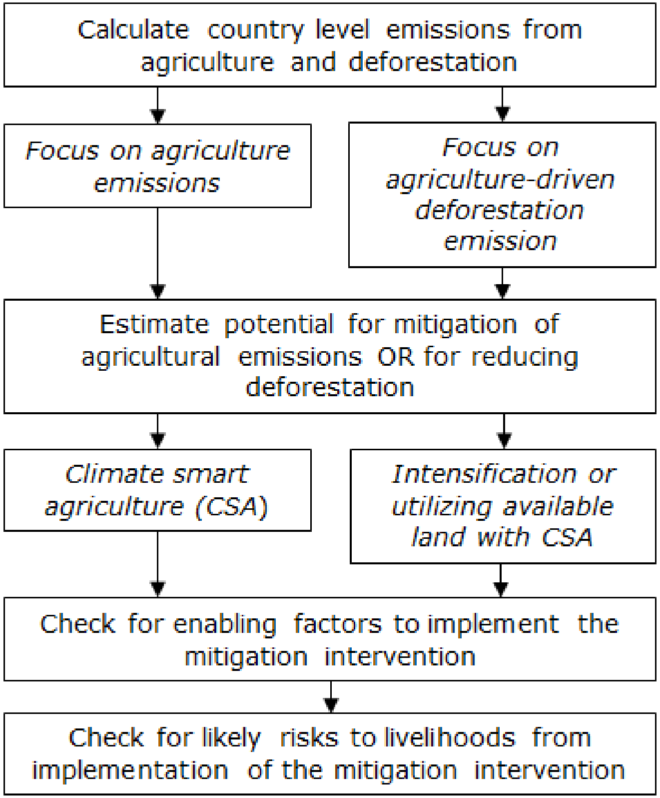

Figure 1. National-scale assessment of the need, potential and risk of implementing interventions to reduce emissions from agriculture and agricultural driven deforestation.

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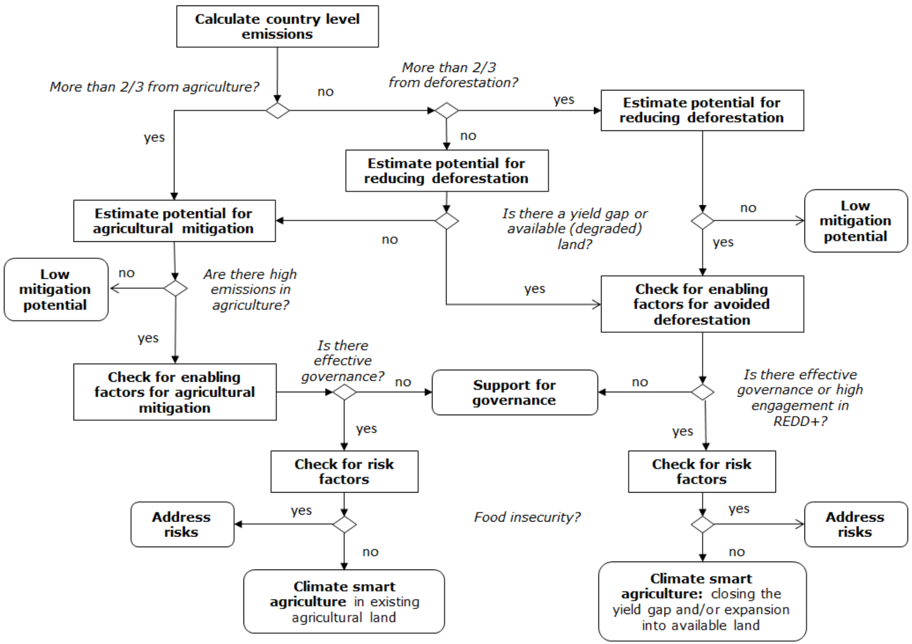

Figure 2. Decision tree to identify priority areas for mitigation interventions. Data required for decision making are described in Table 1.

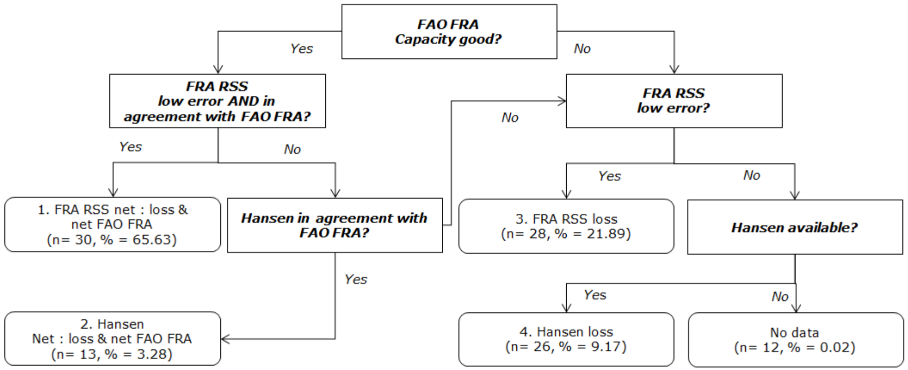

Figure 3. The decision tree for the selection of deforestation data. The decision numbers represent "quality flags", 1 for the highest quality data and 4 for the lowest. N = number of countries in that group, and % = percentage of forest in that group.

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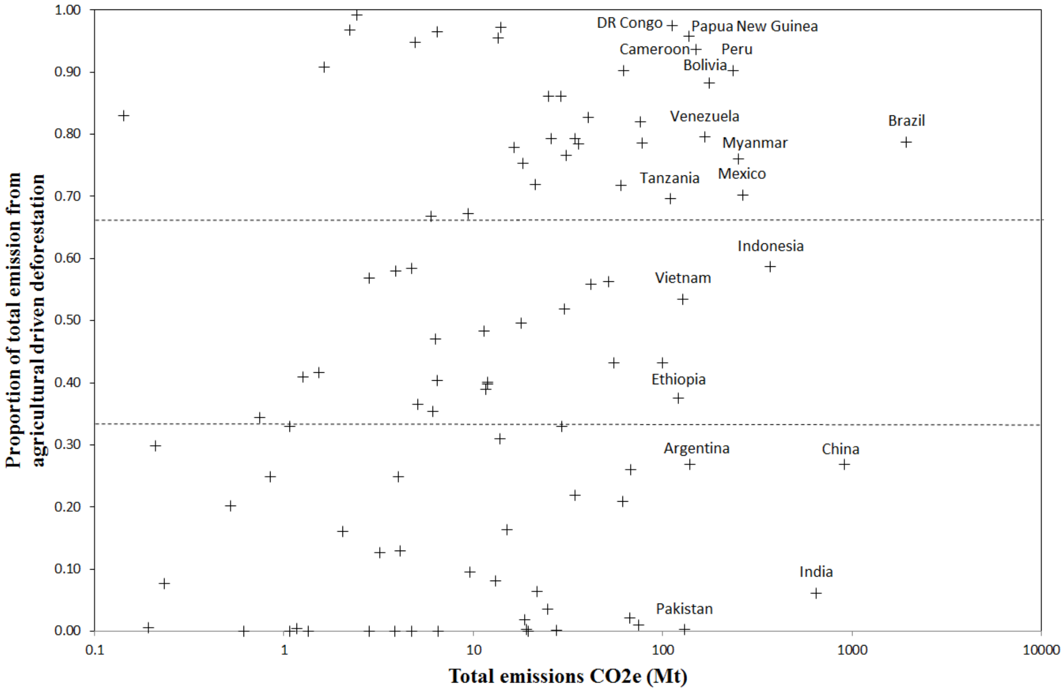

Figure 4. Total CO_2 eq emissions (annual AGB and BGB removals on forest land converted to agriculture (2000–2010/12) plus annual agricultural emissions (2010)), and the proportion of the total emissions from agricultural driven deforestation (1 = 100 % emissions from agricultural driven deforestation, 0 = 100 % emissions from agriculture). The 17 countries with emissions > 100 Mt are labelled ($n = 95$). The horizontal lines distinguish the groups where total emissions are: > 66 % from agriculture (lower third), 33–66 % from agriculture-driven deforestation and agriculture (middle third) and > 66 % (middle third) from agriculture-driven deforestation.

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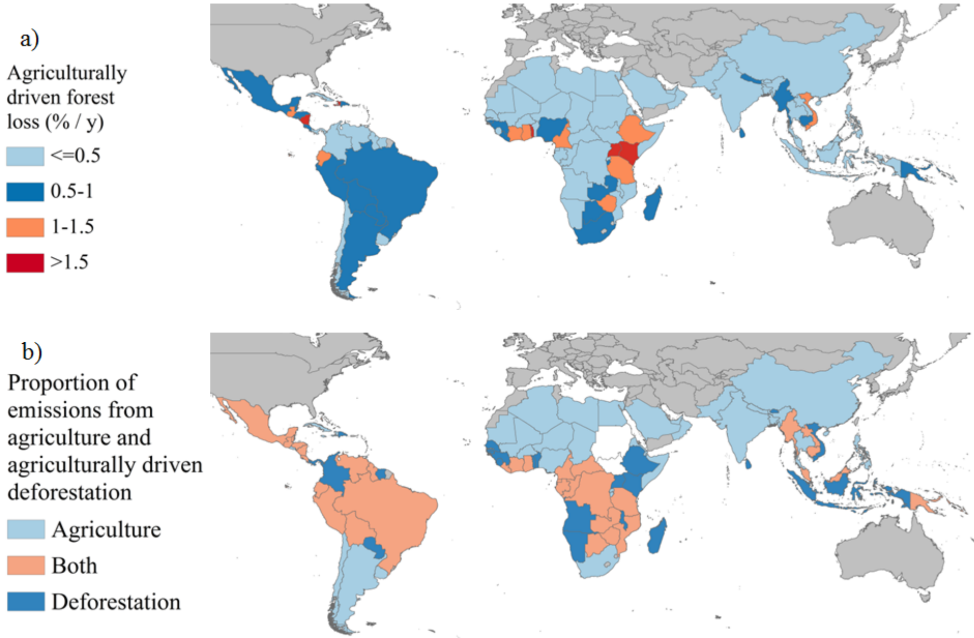

Figure 5. Emissions sources **(a)** % agriculturally driven forest area loss **(b)** proportion of emissions from agriculture and agriculture-driven deforestation (expressed as a proportion of the total emissions "agriculture" = > 66 % from agriculture, "both" = 33–66 % from agriculture-driven deforestation and agriculture and "deforestation" = > 66 % from agriculture-driven deforestation). Grey areas are outside the study area, and white areas had no available data.

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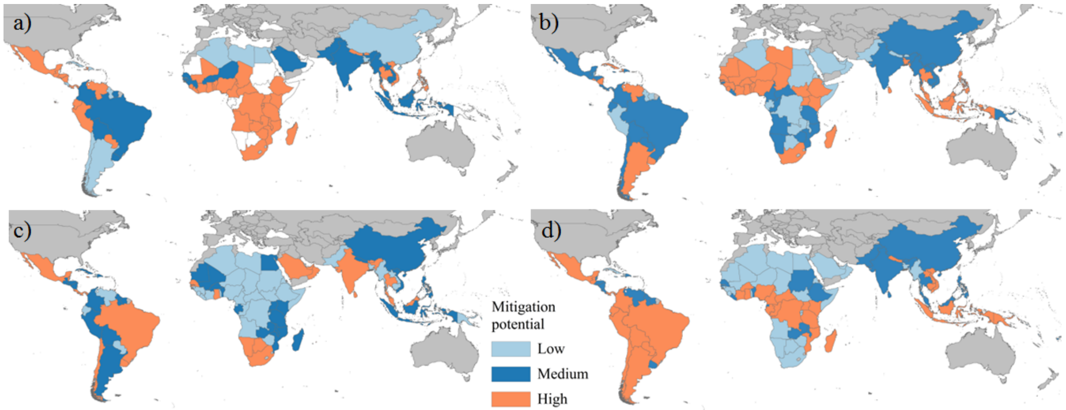

Figure 6. Mitigation potential through **(a)** closing the yield gap, and **(b)** utilizing available land, and enabling environment through **(c)** governance and **(d)** REDD+ engagement. Grey areas are outside the study area, and white areas had no available data.

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