Response to: Editor's decision
Article: Mitigation of agriculture-driven deforestation in the tropics: comparing land-sparing options at the national level
MS No.: bg-2015-79

The authors thank the editor for the decision to publish the article. As agreed, the responses to the reviewers' comments were incorporated in the article and in addition the two points from the editor (below) were also taken into account.

Editor: "Your responses to the reviewers' points have been properly dealt with. On my side, and just for clarification purposes I would suggest you to explicitly include the definitions of 1. mitigation potentials (since there is an IPCC definition of these terms, under a climate change context, that does not necessarily match yours https://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_appendix.pdf) (e.g. your mitigation potentials include no cost and no technical assessments), and 2. yield gap."

Authors: A definition of the mitigation potential has been incorporated into section 2.2, and a definition of yield gap (specifically potential yield), has been included in the introduction.

Response to: Referee comments, Cheikh Mbow, ICRAF, World Agroforestry Center, Nairobi.
Article: Mitigation of agriculture-driven deforestation in the tropics: comparing land-sparing options at the national level
MS No.: bg-2015-79

The authors thank the reviewer for the detailed and insightful comments. These comments will help us to improve the manuscript. Our responses to specific points from the review are detailed below.

Reviewer: This study addresses the importance and potential of forest sparing as a pathway for significant abatement of greenhouse gases (GHG) from land use change. The authors suggested a systematic framework as a common entry point to addressing multiple sources and possible sinks for carbon dioxide (CO2) mostly from the agricultural sector. They hypothesized that improving farming such as agroforestry, climate smart agriculture (CSA), sustainable intensification and similar land management systems will spare forested lands from human pressures and henceforth improve carbon sequestration. The paper is very ambitious in scope and geographical coverage (tropical countries) but the method to achieve the goals quite appropriate. They used mostly secondary data and global databases for their calculations and assessment. Some proxies such as risk was based on food security indices, the least that can be done in assessing social vulnerability and likelihood for relying on natural capital for survival. Similarly baselines forest trends was depicted from conservative approach of past deforestation rate. **Overall the methodological choices are very robust but the analysis could be seen as partial as the authors did not consider non-CO2 GHG.**

Authors: Although our study considered only CO2 emissions due to deforestation, we did consider N2O and CH4 from agricultural emissions but reported CO2 equivalents. This point was clarified in the updated manuscript. Not including non-CO2 gasses in deforestation emissions is a commonly used approach (i.e. Achard et al., (2014)) , but the impact of this on the final results is mentioned in the discussion section (4.2).

Reviewer: The assumption that improved mitigation is related to good governance systems could be scrutinized more in this study. General governance systems does not always reflect those specific to the agriculture and forest sectors. We are in most cases dealing with polycentric governance systems that sometimes oppose various logics and in many instances competing goals. An example is the often cited in the case of inconsistent policy objectives between agricultural development and forest conservation.

Authors: The discussion on this point was be expanded in section 4.5 (second paragraph). The link between good governance (at the national level), and implementation of policies (including at the sub-national level) was included. The complex nature of the issue, and potential for conflicts between different levels of government is discussed in the conclusions. In addition, the conclusions were adapted to note that coordination between agencies is required with consideration of competing goals.

Reviewer: Another limit could in the requirements for a full accounting of the carbon equivalent balance. Many authors recognized that full GHG budget is quite difficult to perform in developing countries because of lack of data (Valentini, R. et al. 2014).

Authors: The limitations / reliability of the input datasets, and the impact on results has been addressed and considered by the authors throughout the methods, and in the discussion.

Reviewer: I fully approve the use of the forest transition curve to support selection of criteria and trend in deforestation but in developing countries there are many possibilities for future tipping points on the natural resources demand as population grows and emerging lifestyle emerges with increased urban population. The emerging demographic and economic situation could lead to more pressures on forest resources but in some instance this could lead to improved forest management with emerging demand for healthy life styles.

Authors: The authors agree that there are many limitations to the use of the forest transition curve to predict future deforestation. In this case we did not use the FT curve in the deforestation estimates. The comments also point to some limitations to the selected methodology, however this is already elaborated in the paper (section 4.3).

Reviewer: Finally is important to question how under current and future socio-ecological situation land-sharing with CSA, agroforestry, and sustainable intensification will contribute to overall climate dynamics, and how high subsidies agriculture could lead to more forest sparing but with more ecological and climate footprints. Those aspects could be the subject of another paper.

Authors: This is indeed a good point, but as the reviewer mentions, is beyond the scope of this study.

Reviewer: The focal interest of this paper is on land based mitigation. It is important to recall the readers that Agriculture, Forestry and other Land Uses (AFOLU) a now a specific section within IPCC AR5 (Chapter 11 of WG III). The conclusion of the IPCC assessment shows that AFOLU offers many flexible options (Smith, Bustamante et al. 2014) that the other sectors do not have. These options have different abatement rates but also different costs. It is important to address the issue of trade-offs amid strategic land based mitigation option but also between those and other aspects of sustainable livelihood and development needs.

Authors: The relevance of this study to the AFOLU sector is mentioned in the paper, however the need to select the most efficient (based on abatement rate and cost of implementation) option within this sector is not discussed in detail. Although estimates on the cost of avoided deforestation, and on mitigation in the agriculture sector are available, since we do not discuss specific technologies (i.e. technologies for intensification), we decided not to discuss the costs of these interventions.

Reviewer: The authors confirmed that agriculture is the main driver of deforestation in tropical area and yet one of the biggest emission sources. The solution for mitigation should be mostly in agriculture not only emission related to deforestation but also emission nested to agriculture systems themselves and food nets. The paper highlighted that land-sparing interventions can potentially be implemented under REDD+ to mitigate the land related emissions. I am not sure if REDD+ is the "silver bullet" solution for reducing GHG, rather additional efforts in non-forested zones through improvement of tree cover, mostly in farming lands could be central to the global solution for land based mitigation strategies. The challenge in developing countries is to meet GHG reduction needs—in the context of Intended Nationally Determined Contributions (INDCs)—without sacrificing food security or natural ecosystems, a challenge called agricultural intensification. Exploring such sustainable intensification pathways should lead us beyond REDD+ that emulates more the countries with dense forest cover. This argument appears in water marks in the paper when the authors stated that deforestation rate as compared to forest cover is higher in non-forested countries (e.g. authors cited Togo, Zimbabwe). Why then too much focus on dense forest countries? (Mbow, C. et al. 2012, Mbow 2014).

Authors: It is true that land sparing interventions may not be best implemented under REDD+ and that other options should be considered. Other interventions include the establishment of protected areas plus implementing the restoration of degraded lands (for example the Global Restoration Initiative[1]) or introducing extension services to promote climate-smart agriculture (or agricultural

[1] http://www.wri.org/our-work/project/global-restoration-initiative

intensification) are also possible. Agroforestry which achieves the aim of carbon storage through sequestration, but not necessarily the protection of established forests is also promoted through a number of other channels, such as through the work of ICRAF. Initiatives are increasingly driven by producers, and interventions like the Roundtable on Sustainable Palm Oil[2] can also reduce deforestation. The point which should be highlighted is that without active forest protection, any efforts to intensify agriculture or to utilize unused or degraded land may not spare forests. This connection is described more clearly in the paper in section 4.5.
The comments on the selection of priority countries by focusing on those countries with dense forest cover (or high levels of carbon stored in forests) is very relevant. Since we consider the mitigation potential of each country in terms of emissions rather than forest area, this is something to be aware of. Deforestation in low density forests in Africa is included in this study provided they meet the FAO forest definition (10% canopy cover etc.), so most of these savanna type systems are included. Togo and Zimbabwe are highlighted as countries with high forest loss due to agriculture in percentage terms. Despite having forests which are relatively less dense, they are still considered priorities for interventions, which shows that our paper uses different criteria than for example REDD+ investors to select countries for interventions. The references provided by reviewers elaborate on this well, and one citation was added to the paper, and a discussion point added to cover this issue in section 4.1, paragraph 1.

Reviewer: The fundamental and technical challenge is how to implement intensification in existing farming lands to avoid net positive emissions including those related to deforestation and low ecological footprint. How to achieve negative emissions through land management systems? Knowing that high inputs and energy intensive agriculture will lead to more emissions (Smith, Haberl et al. 2013)

Authors: This is indeed the fundamental question, and in this paper we take the assumption that this is indeed possible. The methods (for example which interventions to use where) are not discussed as this is not the objective of the paper, but we do conclude that it is possible to lower the emissions intensity of production. This is also discussed in the Smith et al. (2013) paper, who includes options such as the distribution of inputs from low to high fertilized areas. Although perhaps this example is limited in its application, there are other options available, many discussed by the CSA community.

Reviewer: The merit of this paper not only on the research insights (potential for reducing GHG emission from improved land use) but also on how to close the yield gap. **I would wish to add some discussion points on what non-forest lands are used for in developing countries.** Not all lands need to be used for agriculture. Some are spared for ecosystem services, and many for grazing. The potential farming lands issue reminds the assumption made by FAO that Africa is among the continent where existing land suitable for agriculture is among the highest. That was an open gate for land grabbing rather than improving agriculture for and limiting deforestation (Mbow and C 2010).

Authors: For clarification, we include grazing as part of agriculture. It is likely be that our definition of land availability is not complete, however, we do discuss the limitations of this dataset in the paper. Land grabbing (which is mainly for agricultural purposes[3]) fits in well with the discussion here, and the availability of land in parts of Africa is shown in our findings. The authors included the suggested reference, and discussion point in section 4.4.

Reviewer: The paper is very rich in content, well organized and quite inspiring for solution oriented climate decisions. The general observations above is simply to contribute to the debate and highlight

[2] http://www.rspo.org/
[3] http://www.landmatrix.org/en/

the bold value of this paper and why it needs to be read. In few details below I raise some minor aspects that could help orient future thinking or even improve the next paper of this wonderful group.

Scientific questions and specific comments

Specific questions arise when reading the paper. One is the perpetual quiz of emission factor. While we know how many 1 kg of carbon will be released by 1 kg of wood, the oxidation processes leading to carbon emission are very diverse and difficult to assess in a GHG budgeting effort. For instance, fires related emission is difficult to estimate because of varying emission factors depending to burning completeness, the fuel models in presence and the fuel moisture during combustion. If we had a good database of emission factors, knowing area affected by deforestation in exact terms is impossible because of method discrepancies and land cover definitional implications.

Authors: The use of emissions factors is by nature a limitation in the study. The decision not to include burning in the deforestation related emissions estimates is due to a lack of available data on this. The fact that burning has been omitted was included in the manuscript in section 4.2.

Reviewer: In this study as in most similar ones, there is not accounting of carbon sequestration through improvement of tree cover in farming lands is important (recovery areas). Maintenance of forest can help avoid emission from deforestation but will not increase substantially carbon sequestration. Trees and soil carbon sequestration can be increased through promotion of trees outside forests.

Authors: This is indeed a good point, and it does highlight the need to include these emissions reductions when considering different options in practice. The mitigation potential may therefore be underestimated in this study, however the bias is present for all countries, so the results would not differ because of this. The lack of a global dataset on trees outside forests also presents problems to include this in our study.

Reviewer: Another question is what do we do about “non-regret” options such as national parks and protected forest that spare emission from agricultural encroachments with or without REDD+? REDD+ is not fully addressing agriculture even if that sector explain the great deal of deforestation. There is a paradox that makes agricultural intensification—a way for reduced deforestation—as non-REDD+ strategy. CSA is a good mitigation option if implemented well but cannot be a REDD+ branded activity. Agroforestry can be a good mitigation option but up to now there is now REDD+ project based on agroforestry….? Reducing emissions from land use require more inclusion of such practices. A good recommendation is to include land sparing in REDD+ but not at the expense of food security.

Authors: This comment captures the need to maintain forest cover, while considering food security. CSA and Agroforestry cannot be included as REDD+ activities (in terms of the emissions accounting), but they can be potentially included as supportive interventions – i.e. interventions which mean ensure the success of a REDD+ project.

Reviewer: On the technical side, methods for GHG accounting differ in precision and level of disaggregation of various components and process of carbon budget. Current scientific knowledge shows various disaggregation approaches based on land use/cover types from fine scales (Brink, A.B. et al. 2009) to global biomes based carbon accounting (Quéré, C. et al. 2012). The complexity of the carbon cycle in particular in Africa requires in situ data and up-scaling of these data at regional scale. **Until methods and data are improved it will be very hard to accurately (big uncertainties) know when a country has a high potential for mitigation?**

Authors: The authors agreed that it is difficult to know where the highest potentials are for mitigation, however in our case mitigation potential is mainly from avoided deforestation, and we confident about the activity data and emissions factors used in this paper for this process.

Reviewer: Technical corrections

The authors 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. Hansen Data I believe do not use the exact forest definition as FAO did. Also the data work best in pure forest cover biomes. In non-forested lands with trees Hansen maps does not work well (e.g. open savanna or pasture lands). FRA RSS was based on tiles of Landsat data with regular intervals (1 degree interval, 2055 tiles for Africa, 1230 tiles Latin America + Caribbean and 741 tiles South and Southeast Asia). The Sample size is 20 km x 20 km. Then land cover maps and land use maps were based on e-cognition clustering (multi bands, multi years) of small spectral classes using expert knowledge. Regional workshops for validation have been performed to finalize the land and land cover products. The challenge of FRA-2010 data is the status of LANDSAT acquisition under humid forest with a lot of cloud cover that prevent obtaining cloud free data. A big deal of land use emission come from these area where few optical images can be achieved because of “permanent cloud cover” (Roy, P. et al. 2010). The minimum mapping unit of 5 ha, while most land use process happen at small holders plots below the acre in size.

Authors: These comments are correct, and there are a number of limitations to the remote sensing datasets which are described in the paper. Regarding the accuracy of the datasets, we do not go into detail on this, as a full comparison of the datasets is beyond the scope of this study, but we discuss the use of the data and which datasets best meet the needs of the study. For this purpose we consider it sufficient. It is inevitable that any datasets used have limitations, and the authors feel that they have used the best available datasets for the purpose of this study.

Reviewer: For risk assessment the authors used food security index. **Risk is related to 3 pillars: hazard (climate, economic), the vulnerability (poverty, food security) and exposure (how many people, infrastructure etc.). Here only one dimension of risk is taken in relation to food security. I am a bit worrying about the assumption of risk in the paper.**

A part from the general and specific comments made on this paper, I believe the article needed to be written to clarify many issues related to the performance of land based mitigation and context specific feasibility of such options. I was delighted to be appointed as a commentator and well open for subsequent discussions on the issues raised in this short review.

Authors: The authors agree that risk is complex and food insecurity alone does not equal risk from interventions in the farming sector. However there are several reasons why this indicator has been selected. Firstly, because food insecure communities are likely to have less resilience to changes to systems. They are likely to also be income and asset insecure, which also lowers resilience to changes. Where communities are reliant on agriculture for food and/or income, then those who are food insecure are by nature more at risk from potential negative consequences of the intervention in the agriculture sector. Secondly, there are no data on the numbers who would be influenced (exposure) as the interventions are hypothetical. An indicator such as percent of population living in rural areas was considered[4], but there is no clear link between this and those who would be impacted if interventions in the farming system were implemented. Thirdly, the hazard element of risk in our case, is constant across all countries, since we hypothesize that the intervention will occur, and we assume that there is a potential negative impact. There are a number of other hazards which could have both positive and negative influences on a community (such as climate change) and due to complexities, feedbacks, etc. we cannot account for them all. In our case, we take a simple, but we

[4] http://data.worldbank.org/indicator/SP.RUR.TOTL.ZS

believe robust approach, and use vulnerability to change (as indicated by food insecurity) as being the measure of risk. The methods have been expanded substantially to reflect the reviewer comment on the components and complexities of risks, to explain which aspect of risk this study considers (section 2.5).

Response to: Second referee comments, anonymous.
Article: Mitigation of agriculture-driven deforestation in the tropics: comparing land-sparing options at the national level
MS No.: bg-2015-79

The authors thank the reviewer for the helpful remarks. These comments suggested improvements to the manuscript which were made by the authors. Our responses to specific points from the review are detailed below.

Reviewer:

Major Comments:

The authors of the study "Mitigation of agriculture emission in the tropics: comparing forest land-sparing options at the national level" carry out a highly integrative, policy relevant study on the potential for mitigating greenhouse gas emissions through the prevention of deforestation. The authors provide a very interesting analysis that ultimately identifies and prioritizes the most feasible emission reduction options for different countries based on their land use and governance regimes. The study is very timely from both a research and a policy standpoint (it takes advantage of a number of products and demonstrates the integration of interdisciplinary data sources, and provides information that is useful for policymakers prior to the upcoming COP21 negotiations).

This high-level study should be of interest to readers of Biogeosciences. The authors have laid out all of the components of their study in a manner that is extremely clear (both in written form and through flowcharts) and easy to follow, and the approach seems generally sound, though one major comment and some specific comments are mentioned below.

A limitation of this study is that the authors seem to assume zero carbon emissions from the conversion of non-forested land, which may overestimate the mitigation potential of converting this land versus forest. For example, on Page 5438, Lines 11-16, I worry that the authors are, somewhat implicitly, presenting a rather black and white view here of the forms of land conversion that are of concern from a mitigation viewpoint. It is important for the authors to discuss this by, for example, considering the results of studies like Searchinger et al., 2015 ("High carbon and biodiversity costs from converting Africa's wet savannahs to cropland" in Nature Climate Change). In addition, converting land has other costs, e.g. loss of biodiversity that go largely unrecognized in this version of the manuscript.

Authors: The authors agree that this is a very important point. However we choose not to account for emissions which will be created for any interventions which are suggested by our study. There are several reasons for this. Firstly, we focus on the mitigation of emissions from forests, and accounting these emissions. Secondly, we don't propose specific interventions, only consider if a suite of possible interventions would be feasible. This is the case for both interventions which intensify agriculture, and also those involved in utilizing available land. There are a number of possible ways which land can be rehabilitated- depending on the intended use, so it is difficult to consider all the possible options at the scale used in this study. Thirdly, we don't propose a specific location for these interventions, and depending on the selected location, the emissions calculations would differ. Since the authors consider this a very important point, the discussion was adapted to include a discussion on the emissions from the conversion of available land to agriculture in section 4.5.

Reviewer:

Specific Comments:

Abstract, final sentence: Can the authors offer a more specific recommendation or put the issue in context by bringing some information that is in the body of the study up to the abstract? For example, are the forestry and agricultural sectors excluded from national mitigation policies?

Authors: the authors accept that this was a vague sentence, and have amended it reflect the intended point, which is that the agriculture sector must be included in decisions on mitigating forest emissions (which are typically confined to the forest and climate change relevant government agencies) and vice versa. National targets for mitigation that do not consider both sectors at the same time will be difficult to implement at sub-national level, where land use planning considers forest and agriculture together.

Reviewer: I understand that the authors want to provide national-level estimates, but the presentation and use of a national yield gap value seems quite uninformative. I suggest the authors provide some information of the range in this value since sub-national yield and yield gap data are available, and since yield gaps can vary considerably within a country.

Authors: This is indeed a valid point, and the authors will provide the mean and standard deviation yield gap for each country for the three cereal crops in a table in the supplementary materials. However all the variables can vary within and across countries (including deforestation itself), so we choose not to go into in-country variability in the analysis. The aim of the paper is to look at a between-country analysis to identify potential for mitigation, so for this an average country yield gap is informative. It is of course true that the detail is lost, but this should be considered at the project/implementation level (which is mentioned in the discussion).

Reviewer: Page 5439, Lines 22-24: I found this sentence confusing. **Authors**: this will be rewritten as follows.

"It is possible that synergies occur between closing the yield gap and utilizing available land that can provide benefits when both mitigation approaches are implemented within the same country. However, in this study we assume there is potential to mitigate agriculture-driven deforestation when either one of the two approaches is feasible, and we do not consider any mitigation benefits in countries with potential for both approaches."

Reviewer: Page 5440, Lines 3-5: I don't quite understand what you're trying to say here about your use of thresholds. **Authors**: this will be rewritten as follows:

"Countries were divided into three groups using each data source, and groups were defined by dividing the data at the 1/3rd and 2/3rd percentiles. Percentiles were calculated using all the countries with available data for that data source within the tropics (Table 1)."

Reviewer: Pages 5442-5443, Lines 23-6: Please restructure this paragraph a bit, it is hard to follow. **Authors**: this will be rewritten as follows:

"According to the method used in Harris et al. (2012), we calculated emissions by multiplying the area of forest loss by an emissions factor. For the biomass emissions factor, we use the sum of above ground biomass (AGB) and below ground biomass (BGB). We averaged two 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 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 dataset available. The mean AGB in each country was calculated in forested areas, which were selected using the ESA Global Land Cover

map of 2010 developed in Climate Change Initiative (CCI) (ESA, 2013). BGB was calculated from AGB using tree root to shoot ratios equations (Mokany et al., 2006)."

Reviewer: Section 2.2.2 and Table 3: Why did the authors choose 3.5 t/ha as the threshold? I understand that the authors acknowledge this limitation in section 4.4, but it would be more accurate if they changed this value for each country based on the dominant crop, since, for example, the average yield for wheat in a productive area is different than the average yield for corn or rice. Would something like this be feasible for the authors to do/can they do a test to see whether doing this would significantly change their results?

Authors: The selection of 3.5 t/ha was based on the thresholds in the dataset of potential crop yields, and was seen as a useful determinant of 'reasonable' yields. A better analysis would involve potential for specific crops, which would include the most suitable crops for each country (datasets are available for rain-fed wheat for example). However the authors decided that only selecting certain crops would potentially label areas as being unsuitable, when a crop which is not included would be able to provide high yields. Lack of data is the limiting factor in this case. In addition, since within one country there may be some areas where the dominant crop was not suitable, but other crops would be suitable (for example highland / dryland areas), they also may be misclassified as unsuitable. For these reasons we choose to use a dataset which gives an indication of the potential for a more inclusive system which is an average yield of 'rainfed agriculture', rather than focussing on a few crops only.

Reviewer: Page 5444, Section 2.4: Please provide more information on the food security assessment and how it relates to mitigation interventions. Otherwise, it is hard to understand how "Food insecurity indicates a risk to livelihoods when implementing mitigation interventions. . ." later on in the paper.

Authors: The methods section on risk assessment (section 2.4) has been expanded to explain the components of risk which are being assessed in this case. In addition the introduction has been expanded to explain how livelihoods may be at risk from land-based mitigation approaches, and how food insecurity can be a measure of vulnerability to this risk.

Reviewer: Page 5446, Lines 12-15 and 17-20: It is a bit hard to distinguish the difference in the points you're trying to make with these two sentences. (Similarly, the first sentence of Section 4.1.2 is confusing.) Also, given the issue presented with the Haiti example, perhaps the authors could also present the absolute number of hectares of forest loss in addition to the percentages that are relevant to each respective country?

Authors: This is an interesting point. The authors agree that the point is missing in this paragraph, and it has been rewritten (below). The supplementary information shows the absolute area of forest lost to agriculture for each country so this is available for readers.

"*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 km2 y-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). Haiti is an exception which has a high forest loss due to agriculture (>2% y-1) but most emissions are from the agricultural sector due to the small forest area remaining (1090 km2 in 2000, ~4% of the country area)."*

Reviewer: Section 4.3: To be sure, do the authors truly intend to make predictions, or do they intend to make projections with this study? They should double-check their language here.

Authors: According to the IPCC (in the context of climate change) "A projection is a potential future evolution of a quantity or set of quantities." This definition matches with the aims of our paper, so as suggested by the reviewer, we choose to change the wording in the manuscript. In order to look at mitigation potential (which is based on avoiding future emissions) we must estimate future emissions.

Reviewer:

Technical comments:

Abstract, line 22: I believe you meant ". . .there is a potential to mitigate 1.3 Gt. . ..”?
Authors: Changed

Reviewer: Abstract, line 25: delete comma. **Authors:** Deleted

Reviewer: Page 5440, Line 17: At this location, as well as all locations in your paper, please be sure to define your acronyms before you use them. **Authors:** Acronyms defined

Reviewer: Page 5444, Section 2.3: Where did the authors acquire the governance data to calculate the index – from World Bank, 2012? It was difficult to tell whether the index algorithm or the index algorithm and the data were acquired from this source. **Authors:** This has been clarified in the manuscript.

Reviewer: Page 5454, Line 6: I think you meant "within the range of those", and Line 17: I think you're missing a word in this sentence as it is awkward. **Authors:** The suggested changes have been made.

Reviewer: Page 5455: It should read ". . . the soybean industry's. . ." **Authors:** Changed

Reviewer: Page 5456: "can be mitigated in those countries in which 33% of emissions are produced by agriculture. . ." **Authors:** Changed

Reviewer: Table 4: The authors should add in some additional lines to delineate the rows from one another, otherwise it is difficult to read. **Authors:** Changed

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

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Abstract

Emissions from agriculture-driven deforestation are of global concern, but forest land-sparing interventions such as agricultural intensification and utilization of available non-forest land offer opportunities for mitigation. In many tropical countries, where agriculture is the major driver of deforestation, interventions in the agriculture sector couldan 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 between 2000 and 2010. Emissions from agriculture-driven deforestation in the tropics (97 countries) between 2000 and 2010 are 4.3 $GtCO_2e$ y^{-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 awith potential for forest-sparing

interventions~~, and where there is~~ and a good enabling environment (e.g. effective governance or engagement in REDD+), there is a potential to mitigate ~~is~~ 1.3 $GtCO_2e$ y^{-1} (20 countries of 78 with sufficient data). For countries where we identify agriculture emissions as a priority for mitigation, up to 1 $GtCO_2e$ y^{-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 on mitigation interventions. 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 sectors cannot be considered independently. ~~This~~ Our findings highlight~~s~~ the need to include the forest *and* the agricultural sector in the decision making process to~~for~~ mitigate~~ion~~ deforestation.~~interventions at the national level.~~

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1. Introduction

The agriculture and forestry sectors, including deforestation and forest degradation~~,~~ are major contributors of global greenhouse gas (GHG) emissions, accounting for approximately ~~large proportion (ca. 50%)~~ ~~the~~ half of low income countries' total GHG emission budgets (IPCC, 2014). Estimates suggest that global emissions from deforestation were 4.9 ± 0.6 CO_2e~~q~~ 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~~is the only driver 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_2e~~q~~ 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). Agricultural ~~I~~intensification ~~by~~ which reduces~~ing~~ 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~~ contribute to land sparing. The potential yield is the maximum yield given the biophysical conditions – with the absence of any limitations (Neumann et al., 2010). 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.

and was considered as land-sparing intervention in this study. In addition,. In this study we also considered 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.

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 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. There is also a

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. potential for community benefits to accompany agricultural expansion and developments, however they can also negatively affect local communities. Access to land can be compromised, and interventions may not offer equitable distribution of benefits to stakeholders, excluding vulnerable communities (Mbow, 2010).

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~~many 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-driven deforestation, and from agriculture (figure 1). Firstly, we quantify emissions from agriculture-driven deforestation and agriculture in each country. ~~We then~~Secondly, we 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~~ indicate countries which are likely to require increased support to implement mitigation initiatives~~,~~ by assessing their capacity to implement interventions. 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~~ This study considered all tropical (within the tropics, or with a tropical biome) (WWF, 2013) non-annex 1 countries ~~(WWF, 2013)~~ or countries who are engaged in REDD+. Not all had data available to assess the mitigation potential (figure 1), ~~so this analysis covers only~~leaving 78 countries which represent 85 % of the forest area in the tropics for the study.

However, 97 countries had data available to calculate emissions from agriculture-driven deforestation and of those, all but two had no data on emissions from agriculture (n=95 for total emissions), so these results are presented (section 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 (figure 2). We looked 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 occur between closing the yield gap and utilizing available land which that can be exploited benefited fromprovide benefits when both mitigation approaches are by implementeding both approacheswithin the same country. H, however, in this study we assume there is potential to mitigate agriculture-driven deforestation when either one of the two approaches is feasible, and we do not consider any additional mitigation benefits in countries with potential for both approaches. Where agricultural emissions are largest, we estimated the potential to mitigate these emissions is estimated. For countries with a high potential for mitigation, we assessed the potential for a mitigation intervention 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 were then considered. Data Countriessources were categorized were divided into three groups using each data source, and groups were defined by by thresholds at thedividing the data at the $1/3^{rd}$ and $2/3^{rd}$ percentiles. Percentiles , takingwere calculated into account usingaccounting for all the countries with available data for that input data source within the tropics for each variable (Table 1).

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2.1. Calculation of emissions

The source of emissions wasis 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 estimated total deforestation areas from based on 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, for example in the cases of China, India and Vietnam for example, large-scale afforestation projects will mean that gains to forest area will lead to an underestimation ofe deforestation if net data are used (FAO 2010). So far, no single data source exists which provides gross forest change with a forest land-use definition;Since the Forest Resources Assessment Remote Sensing Survey (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 usewe combined remote sensing based forest-cover change data from Hansen or withor FRA RSS to derive a ratio of net forest change to forest loss 'Net:Loss' (Fig. 3). We, and used this factor for to estimateing gross forest loss from the Food and Agriculture Organization of the United Nations Forest Resources Assessment (FAO FRA) data (Eq. 1).

$$Gross\ forest\ loss = net\ forest\ change_{FAO\ FRA} * Net{:}Loss_{Hansen\ or\ FRA\ RSS} \quad (1)$$

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. 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 smaller than the standard error for either the loss or gain in that time period, we did not use the FRA RSS 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 data (Romijn et al., 2012). We used this data only when the country was considered to be 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 (no data was also recorded 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~~For future projections of deforestation areas~~ (since by nature current estimates of deforestation today are based on historic data~~reflect past developments~~)~~, 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~~Here, we considered a period of 10 years~~results to be valid for a period of 10 years~~, which is in line with other studies (e.g. Rideout *et al* 2013).

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 used 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). Indirect drivers include~~ly,~~ international markets and population growth that influence the land change. We used national data from Hosonuma et al. (2012) 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, country profile reports from the 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 quantified~~reported~~ either as a ratio, ordinal, or nominal scale~~, and data, depending on the reporting format in the data source~~. These were scaled ~~between~~ from 0 ~~and~~ to 1 (~~,~~representing ~~from~~ minimal to high influence)~~.~~ ~~This~~, to indicate~~s~~ 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).

$$Agriculture\ driven\ deforestation = deforestation * agricultural\ driver\ factor \quad (2)$$

According to the method used in Harris et al. (2012), we calculated emissions by multiplying~~ied~~ the area of forest loss by an emissions factor~~ to estimate emissions~~. For the biomass emissions factor, we use the sum of above ground biomass (AGB) and below ground biomass (BGB). ~~W~~We ~~e used the~~ averaged ~~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 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 available. The mean AGB in each country was calculated in forested areas, which were~~After~~ selected~~ing~~ ~~areas with forest cover~~ using the ESA Global Land Cover map of 2010 developed in the Climate Change Initiative (CCI) (ESA, 2013).~~, we calculated mean biomass for each country. From AGB, we calculated below ground biomass (~~BGB was calculated from AGB~~)~~ using tree root to shoot ratios equations (Mokany et al., 2006).

2.1.3. Emissions from agriculture

~~National~~ We used national emission data ~~from the FAO are available~~from FAO (2012)~~, and~~ to calculate ~~agricultural emissions we summed~~total emissions from agriculture, covering ~~(~~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 do not account for sinks such as those which occur from crop re-growth. We excluded energy use in agriculture. ~~The definition of~~According to FAO (FAO, 2014a) 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~~Additionally, 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. We define mitigation potential as the total mitigation which could be achieved over time. We do not consider practical constraints (technical potential), or cost limitations (economic potential) (Baede et al., 2007).

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) and therefore, we focus on these three crop types in our analysis~~, 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~~ calculated by the following function (Eq. 3), using yield gaps and production areas of each crop (*x*).

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

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. 1S, in the supplement). These conditions include (1) the biophysical potential; at minimum a moderate rainfed yield, low slope, and not ~~classed as~~ barren and (2) the availability of ~~the~~ land; not forested, not~~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~~ result in an optimistic estimate of available land since socio-economic and regulatory barriers to land cultivation have not been considered.

2.2.3. Potential for reduction of agricultural emissions

Where the majority of emissions are ~~target for emission reductions is~~ in the agriculture sector (Fig. 1), we calculated the emissions t CO_2e per hectare of agricultural land using national emissions data (section ~~2.3.1~~2.1.3), 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 for mitigating deforestation~~,~~ we used two indicators: governance and engagement in REDD+. To indicate governance, we summed the following components of a governance index, available from the World Bank (2012): government effectiveness, regulatory quality, rule of law and control of corruption~~ (World Bank, 2012)~~.

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~~ weighted countries receiving support from the UN-REDD by one~~1~~, and partner countries ~~½. B~~by one-half. There are several steps in the process to gaining an emissions reduction purchase agreement (ERPA) within the FCPF Carbon Fund, so we ~~gave~~ weighted countries who participate (signing a partnership agreement, but yet to submit any documents) by one-third~~1/3~~, countries who submitted the RPIN (Readiness Plan Idea Note) ~~2/3~~by two-thirds, and countries with a finalized R-PP (Readiness Preparation Proposal) by one~~, 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 1S in the supplement). We summed all the scores per country and divided by 7 (the maximum summed score) to create the index for REDD+ engagement 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. Risk is dependent on many elements, which can be grouped into three components: hazard (physical realization of the risk), exposure (elements exposed to the risk) and vulnerability (susceptibilities of the exposed elements) (Cardona et al., 2012). We consider that the hazard (a system change leading to changes to land use) occurs, and that the exposed elements are local communities. We then use a food security index as a proxy for vulnerability, reflecting risk as a whole~~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/).

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 GtCO$_2$ y^{-1} emitted to the atmosphere (Fig 4.). The largest forest loss due to agriculture occurred in Brazil (29,470 km^2 y^{-1}). On average, countries lost 0.52% yr^{-1} of their forest to agriculture, with the highest percent loss in Togo (3.71% y^{-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 of the total emissions (>66%) and (3) agriculture-driven deforestation and agriculture each contribute 33-66% to the total emissions. Those countries where emissions from deforestation are highest i~~i~~nclude those which have high forest losses due to agricultural expansion, e.g., Zimbabwe 1.35% yr^{-1} (2548 km^2 y^{-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% y^{-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 according to their mitigation potential using the decision tree (Fig. 2); ~~, and~~ the main results are presented in Table 4. Out of 44 countries with >33% of the total emissions from agriculture-driven deforestation, 33 countries 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 y^{-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 either >66% of total emissions from agriculture or ~~who had~~ 33-66% of total emissions from agriculture ~~and who had~~and no mitigation potential through land-sparing (Fig. 2) were assessed for the potential to mitigate emissions from agriculture. Of those 38 countries, 12 hav~~ed~~e a potential to mitigate up to 1 $GtCO_2e$ y^{-1} of agricultural emissions. However, only two countries hav~~ed~~e a good enabling environment, and of those only Thailand has low risks associated with the implementation of interventions, so mitigation potential is low.

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~~ a successful implementation of interventions. There are 13 countries ~~which have >~~with more than 33% of their emissions originating from agriculture-driven deforestation, which 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 annual forest lossesest each year which areis driven by agriculture. Converting forest loss to emissions, and also consideringspecifyingcomparing this to the proportion of emissions which come from agriculture allows mitigation approaches for the main source to be considered. We consider emissions to indicate the need for mitigation rather than forest area loss, which gives a focus on countries with high carbon forests. This can lead to highly valuable wooded ecosystems being neglected (Mbow, 2014). However, countries with low carbon forests do appear in our study and are highlighted as priorities for action (e.g. Zambia, Togo).

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. CHowever countries described as havingwith a low potential for mitigation should also be assessed at the sub-national level for opportunities. SpecificallyIn addition, risks should be assessed 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). The likelihood that negative impacts will result is dependent on the safeguarding systems implemented with the intervention (Peskett and Todd, 2013).

We explored three national case studies in more detail, providing recommendations based for the mitigation of emissions from both agriculture-driven deforestation and from emissions infrom existing agriculture al land (Table 5). Two cases represent the potential to mitigate deforestation related emissions (Democratic Republic of Congo (DR Congo) and Indonesia), and one case study highlights the case for targeted interventions within the agricultural sector (Argentina). All countries have emissions >1 Gt CO_2e yr^{-1} (Fig. 2), and have supporting data available to ~~validate~~ evaluate the use of the framework for the assessment of the mitigation potential.

4.1.1. Case study: DR Congo

Emissions from agriculture-driven deforestation in the DR Congo 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~~given the high yield gap, although available land is rated low (~12%). Reports suggest that one of the major barriers to the 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~~Vulnerable communities may be affected by ~~with~~ land based activities, since DR Congo is food insecure. ~~Dependence on r~~Roots, tubers and plantains ~~is more than 50%~~compri~~o~~ise more than the half of the ~~of~~ dietary requirements in the DR Congo~~,~~ and a fall in production over recent years has led to fall in the average caloric intake (Alexandratos and Bruinsma, 2012). T~~his t~~ogether with the country's state of post-conflict recovery this 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

In Indonesia 41% o~~O~~f the total agriculture and agriculture-driven deforestation emissions originate~~s, 41% comes~~ from agricultur~~al emissions~~ e~~in Indonesia~~. Since Indonesia has available land ~~(55% of the forested area)~~approximately half the area of its forests and a relatively small yield gap (2.22 t h^{-1}), the identification of unused land ~~which can be used for growth areas can~~could be explored as a priority. Caution should be taken since the conversion

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4.1.3. Case study: Argentina

~~. 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 to decision making.~~ In Argentina, 73% of the total emissions from agriculture-driven deforestation and agriculture, ~~73% comes~~ originate 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~~ in 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. Successful interventions such as a tax on soybean exports (Kissinger et al., 2012), which are driving land acquisitions (www.landmatrix.org) have also contributed to reduced expansion of agriculture land. 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

Formatted: No Spacing, None, Space Before: 6 pt, After: 0 pt, No bullets or numbering, Don't keep with next 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) use~~s~~ the FRA RSS sample data (see section 2.1.1) and find~~s~~ 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 lower ~~25-50%~~ than~~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)~~,~~ find~~s~~ annual forest loss for 73 tropical countries (excluding the Caribbean) of 36,750 - 143,330 km^2 y^{-1} (with a median of 85,160). This supports our results for the same countries (we estimate 117,486 km^2 y^{-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 between~~in~~ estimates stems~~is~~ from the emissions factors rather than the activity data. Since ~~this paper~~our study uses a comparative approach to assess the need for mitigation on a country level, we consider these data still useful for this purpose. Emissions from deforestation can also be higher than we predict, as these studies do not consider losses from peat soils, burning of the forest or other GHGs.

4.3. ~~Predicting~~ Projecting 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~~projections 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~~may lead to more reasonable estimates. For example, a~~A~~djusting historic baselines based on the forest transition curve (FT) to make projecti~~edicti~~ons 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). Simulation m~~M~~odels 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 across national borders, and partial equilibrium models (e.g. GLOBIOM) are able to model competition for land~~, and incorporate data on~~ by accounting for 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~~ projections 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. H~~, h~~owever, 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 productivity is considered, which can be exceeded by~~ and~~ irrigation~~ can be used to increase productivity~~, (2) the applied threshold for the minimum potential productivity of 3.5 t ha^{-1} can be considered overly conservative, since many areas are cultivated with lower production levels (Droogers et al., 2001)~~. H, 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 likely changes inimpacts of future climate change on crop production (Frieler et al., 2015; Rosenzweig et al., 2014)(Rosenzweig et al., 2014, Frieler et al., 2015), (5) the land cover classes used in the availability criteria imply availability, but can also include some land already in use (56) we excluded slopes above >15%, which can, however, can potentially 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 slopeTYet, the 15% slope threshold however, is commonly used to identify agricultural suitability at large scale 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. Regarding the implied land availability, we acknowledge that some areas may not be available, for example grazed areas may not be in the agriculture land cover class of the land cover dataset. Promoting agriculture expansion in areas which are used by local communities can lead to negative effects (Mbow, 2010). Yet, land availability was , however this dataset is used to indicate the amount of available land not torather than identifying areas for agricultural development, which requires local evaluation including risk assessments. Despite its limitations, comparisons with other datasets support the our method in this paperapproach. Within the tropics we find approximately 8,290,000 km^2 of available land (Fig. 1S in the supplement). This is over 11% of the total terrestrial area. Other studies also suggest that there are large areas of land available globally (references!!) andfor example Campbell et al., 20008(Campbell et al., 2008) finds that over 3.5% of the land area is suitable for bioenergy production when only considering abandoned agricultural land.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). Lambin et al. (2013) calculated available land, and we compared A comparison of three areas for which data are available with our own study, and shows that the areas predicted in this study arethey are within the same region range of those calculated by Lambin et al. (2013) (Table 6). Lambin et al. (2013) used a This is a bottom-up approach to 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 as our findings (Fader et al., 2013).

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4.5. The land-sparing hypothesis

~~Land sparing can only occur if the~~To spare land the yield gap ~~is~~ needs to be sufficiently decreased or even closed, and ~~if~~ available land needs to be~~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~~ improve production can reduce the need to expand agricultural production into forests (Borlaug, 2007; Stevenson et al., 2013). Yield gaps vary within countries (Table. 2S, in the supplement), and areas where yield gaps are highest may be targeted for interventions. 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 can reduce~~avoid~~ emissions, due to a reduced emissions intensity from production (Burney et al., 2010). In order to avoid social and environmental costs of agricultural intensification, 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 (Bajzelj et al., 2014; Kastner et al., 2012).

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). Despite the potential for emissions reductions from utilizing available land, there will always be emissions created from the utilization of these lands (Searchinger et al., 2015). H~~,~~ ~~h~~owever, when weighted against potential deforestation emissions, the carbon balance can be tipped in favour of conversion of available lands. In addition, where available lands are degraded (one of the reasons land is not currently utilized), rehabilitating them can increase the carbon storage capacity of soils, so adding to the mitigation potential (Smith et al., 2008).

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~~soybean 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). Although national level governance may be good, central governments may not support community level actions, so a multilevel system is important (Angelsen, 2010). ~~Nationally Appropriate Mitigation Actions (~~NAMAs~~)~~ can also help to achieve targets of agricultural mitigation, ~~and~~ ~~also~~ can help to reduce leakage risks and foster wider engagement at the country level, and can be combined within REDD+ mechanisms (Kissinger et al., 2012).

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, we have ~~showed~~demonstrated how available data can be used to identify where emissions ~~within the~~from 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). Yet, ~~, but generally~~ there is ~~room~~ potential for improvement to ensure that where agricultural drivers are present, ~~they~~ those are addressed with appropriate interventions within the agricultural sector (Salvini et al., 2014). This task is not without difficulties, since government agencies focussing on agriculture and those focusing on forestry may ~~by nature~~ have differing objectives, and a systematic incorporation of policies is required to consider competing goals. ~~For example, i~~In addition, if interventions are implemented in the agricultural sector to spare forest land, then support from the forestry sector is also necessary to protect existing forests.

Our findings show ~~that there is an existing~~a mitigation potential ~~to mitigate~~of 4.26 $GtCO_2e\ y^{-1}$ 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 $GtCO_2\ y^{-1}$ can be mitigated in those countries~~, who have~~ in which ~~>33%~~more than one third of their emissions stem from agriculture-driven deforestation and which have a good enabling environment (20 countries). These countries~~, which~~ ~~represents~~are responsible for 31% of the total emissions from agriculture-driven deforestation in the tropics. ~~These countries~~They 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~~ mitigation interventions and this should be considered as part of the decision making process. A number of countries have a high mitigation potential but indicators for these countries suggest ~~the~~ a weak enabling environment ~~is not strong~~ (e.g. Angola, Honduras) (table 4). In these cases, long~~er~~-term support which also seeks to build governance capabilities ~~can be considered~~is required.

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~~ a~~u~~nd following the ~~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~~ for other scenarios, or at other scales (for example regional~~,~~ and local~~ for example~~) to ~~set~~ identify priorities for mitigation across sectors in a transparent manner. As new data becomes available, the analysis can be repeated to produce an updated output.

Author contributions

M. H., L. V. and S. C. designed the study, M. H., M. C. R. and S. C. developed the methods, K. N. provided data, S. C. performed the analysis, all authors interpreted the results, S. C. prepared the manuscript with contributions from all co-authors.

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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 (tCO_2e)	Emissions (CO_2) which come from agriculture-driven deforestation (multiple data sources - see section 2.2) and from agriculture (CH_4, N_2O, CO_2) (Emissions from agriculture 2010 [or most recent data point available] [t CO_2e][1] (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_2e 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 section 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

[1] CO_2e – equivalent concentrations of other GHGs in terms of radiative forcing as carbon dioxide.

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 & 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

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

Availability factor	**Availability condition**	**Data description**
Yield potential for rainfed 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)

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	Colombia Guinea-Bissau		Bolivia, Brazil Costa Rica Guyana Cambodia Lao PDR Myanmar

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	Eritrea		
	Jamaica		
	Libya		
	Mali		
	Mauritania		
	Mauritius		
	Niger		
	Nigeria		
	Oman		
	Rwanda		
	Saudi Arabia		
	Somalia		
	Chad		
	Uruguay		
	South Africa		

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

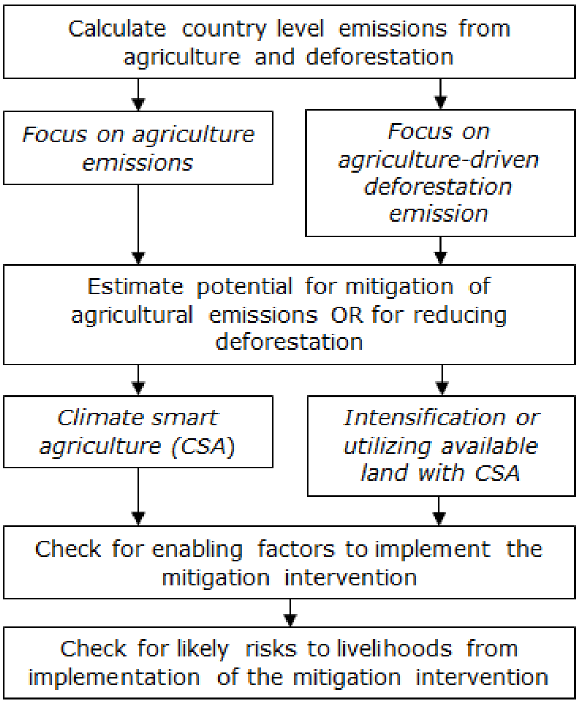
	DR Congo	**Indonesia**	**Argentina**
Emissions source	Deforestation	Both	Agriculture
Mitigation potential	Reducing deforestation	Reducing deforestation	Agricultural sector
Yield gap	High	Medium	Low
Available land	Low	High	High
Agricultural emissions	Low	High	Low
Enabling environment	Yes	Yes	No
Governance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

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

Source	Availability definition	DR	Indonesia	Brazilian and

		Congo		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').


Calculate country level emissions from agriculture and deforestation
Focus on agriculture emissions
Focus on agriculture-driven deforestation emission
Estimate potential for mitigation of agricultural emissions OR for reducing deforestation
Climate smart agriculture (CSA)
Intensification or utilizing available land with CSA
Check for enabling factors to implement the mitigation intervention
Check for likely risks to livelihoods from implementation of the mitigation intervention

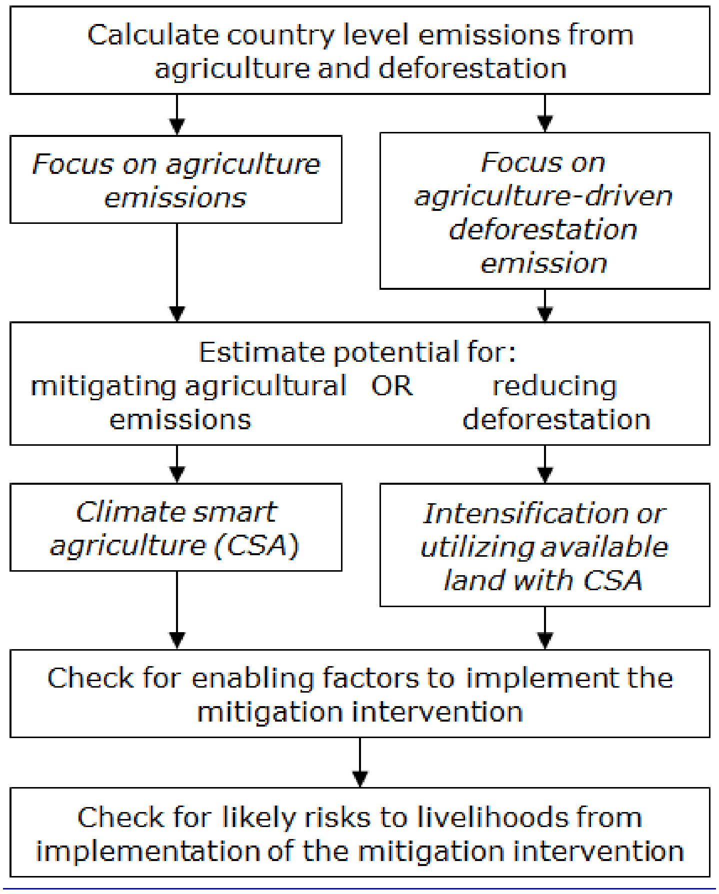


Figure 1. National-scale assessment of the need, potential and risk of implementing interventions to reduce emissions from agriculture and agricultural driven deforestation.

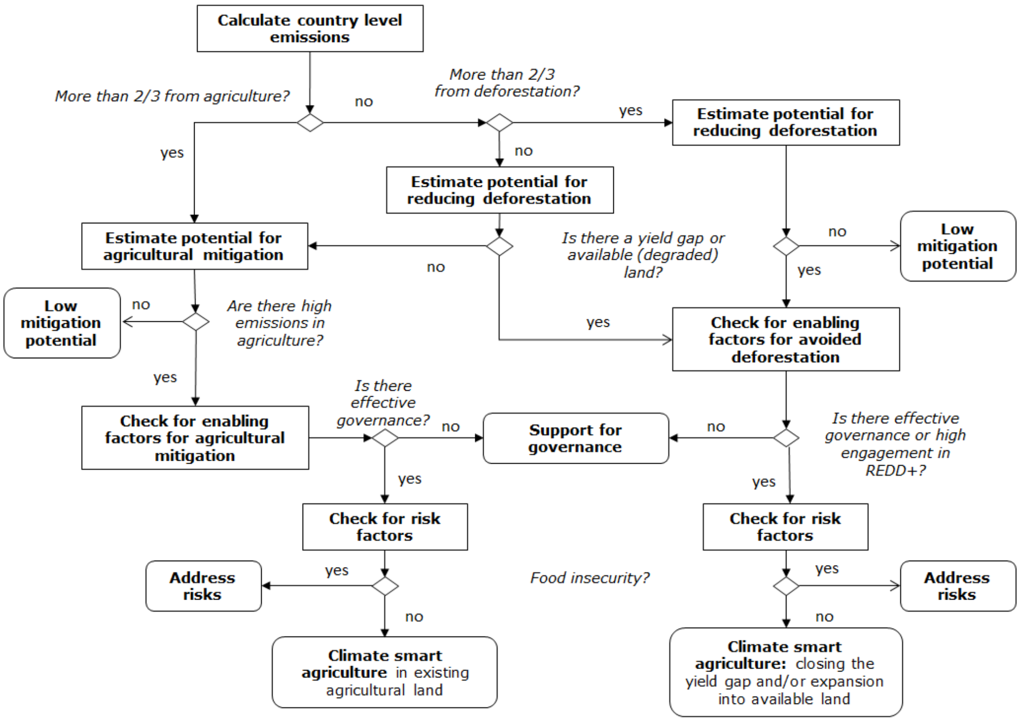


Figure 2. Decision tree to identify priority areas for mitigation interventions. Data required for decision making are described in table 1.

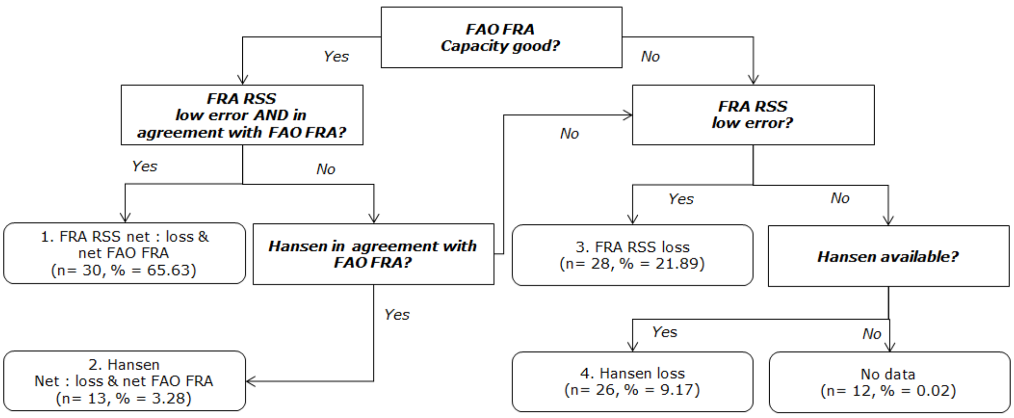


Figure 3. The decision tree for the selection of deforestation data. The decision numbers represent ‘quality flags’, 1 for the highest quality data and 4 for the lowest. N = number of countries in that group, and % = percentage of forest in that group.

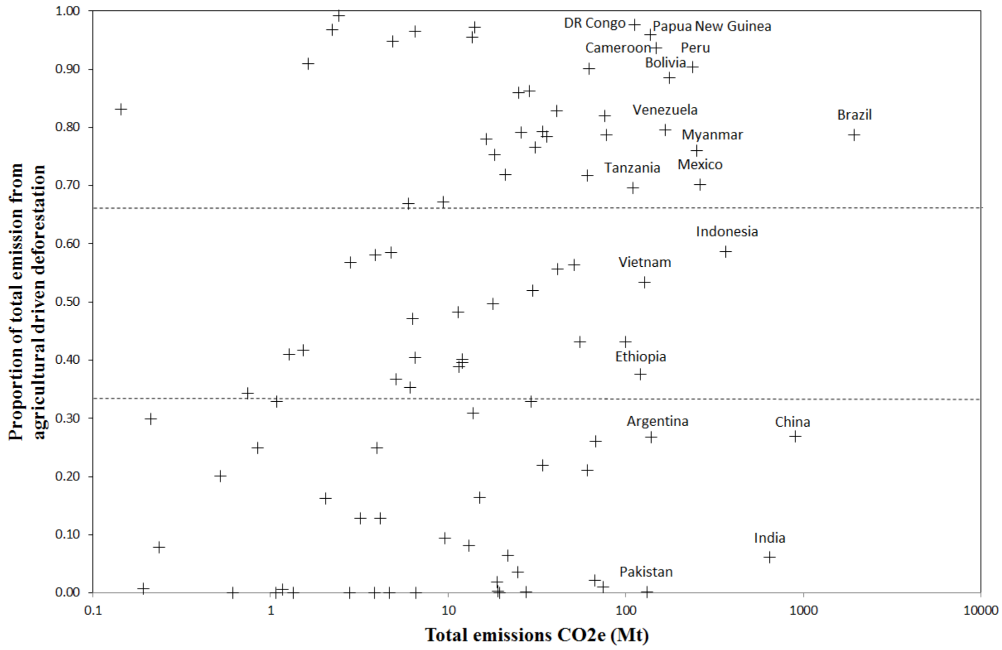


Figure 4. Total CO_2e emissions (annual AGB and BGB removals on forest land converted to agriculture (2000-2010/12) plus annual agricultural emissions (2010)), and the proportion of the total emissions from agricultural driven deforestation (1 = 100% emissions from agricultural driven deforestation, 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.

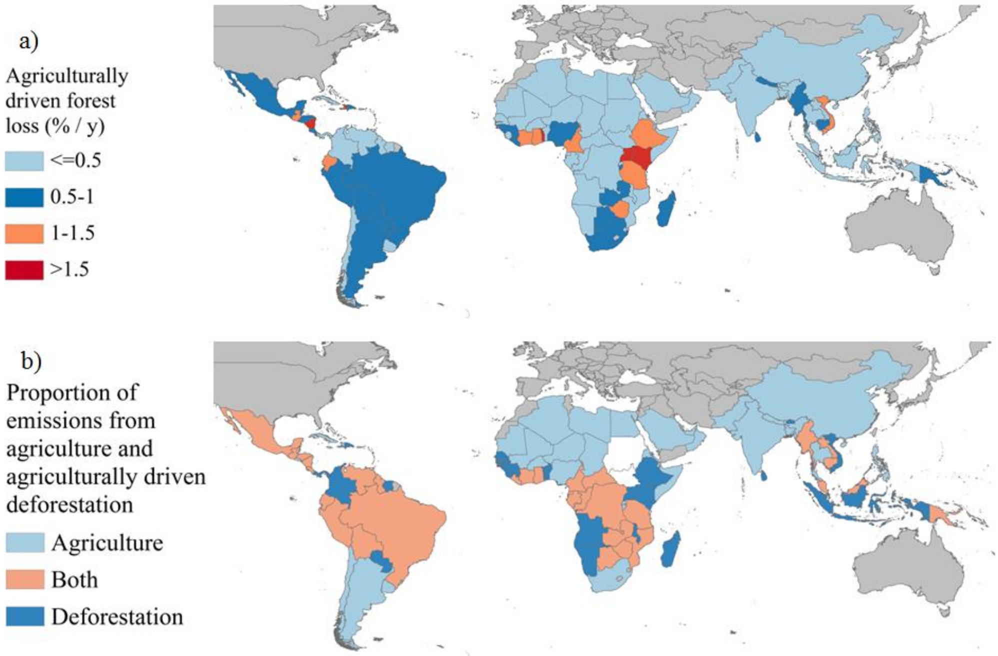


Figure 5. Emissions sources (a) % agriculturally driven forest area loss (b) proportion of emissions from agriculture and agriculture-driven deforestation (expressed as a proportion of the total emissions 'agriculture' = >66% from agriculture, 'both' = 33-66% from agriculture-driven deforestation and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

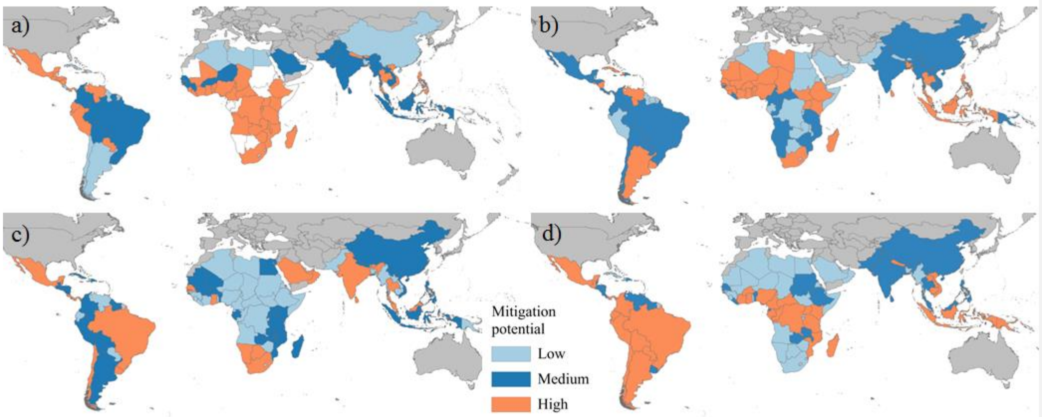


Figure 6. Mitigation potential through (a) closing the yield gap, and (b) utilizing available land, and enabling environment through(c) Governance and (d) REDD+ engagement. Grey areas are outside the study area, and white areas had no available data.

Table S1: REDD+ engagement index created for this study

Indicator		Score
Participation in international REDD+ initiatives	UN-REDD (United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries) – countries receiving support	1
	UN REDD – partner countries	0.5
	FCPF (Forest Carbon Partnership Facility) - a participant (signing a partnership agreement, but yet to submit any documents)	0.33
	FCPF (Forest Carbon Partnership Facility) - submission of the RPIN (Readiness Plan Idea Note)	0.66
	FCPF (Forest Carbon Partnership Facility) - R-PP (Readiness Preparation Proposal) finalization	1
	CIF-FIP (Forest Investment Plan (FIP) within the Climate Investment Funds (CIF))	1
	GEF (The Global Environment Facility)	1
	Governors' Climate and Forests Task Force.	1
Number of projects	0	0
	1-5	0.25
	6-10	0.5
	11-25	0.75
	>25	1
Funding acquisition	0	0
	<6 M USD	0.25
	<11 M USD	0.5
	<100 M USD	0.75
	>100 M USD	1

Table S2: Yield gap (t ha^{-1}), and standard deviation (s.d.) of maize, rice and wheat

Yield gap (t ha^{-1})	Wheat		Rice		Maize	
	Mean	s.d.	mean	s.d.	mean	s.d.
Angola					5.29	0.28
United Arab Emirates						
Argentina	1.14	0.37	1.39	0.21	2.93	0.88
Antigua and Barbuda						
Burundi					5.16	0.52
Benin			3.20	0.72	4.37	0.61
Burkina Faso					2.99	0.25
Bangladesh			1.82	0.55		
Bahamas						
Belize						
Bolivia	1.50	0.71			3.88	1.20
Brazil	1.76	0.38	2.24	0.92	3.24	0.99
Brunei Darussalam						
Bhutan			3.07	0.00	5.37	0.07
Botswana						
Central African Republic			4.08	0.00	3.88	0.03
Chile	2.07	0.96			0.97	0.12
China	1.27	0.82	1.51	0.47	2.90	1.22
Côte d'Ivoire			3.07	0.49	3.94	0.29
Cameroon					4.05	0.87
Congo, DR			4.01	0.87	4.61	0.62
Congo						
Colombia			1.98	1.14	3.91	1.18
Comoros						
Cape Verde						
Costa Rica			1.48	0.25		
Cuba			1.70	0.31		
Djibouti						
Dominica						
Dominican Republic			1.36	0.19		
Algeria	1.63	0.48				
Ecuador			2.63	0.73	4.32	0.69
Egypt	0.39	0.13	0.59	0.05	0.75	0.22
Eritrea						
Ethiopia	1.57	0.27			4.61	1.02
Fiji						
Micronesia						
Gabon						
Ghana					3.93	0.40
Guinea			2.58	0.49	3.92	0.25
Gambia			1.59	0.00		
Guinea-Bissau			2.01	0.44		
Equatorial Guinea						

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Guatemala					4.21	0.91
Guyana			1.71	0.21		
Honduras					4.43	0.60
Haiti			3.10	0.67	4.90	0.47
Indonesia			1.86	0.61	3.48	0.85
India	1.39	0.93	2.28	1.01	3.52	0.88
Jamaica						
Kenya					4.25	0.74
Cambodia			2.18	0.43	3.49	0.47
Kiribati						
Lao PDR			1.72	0.44		
Liberia			3.21	0.72		
Libya	0.96	0.32				
Saint Lucia						
Sri Lanka			1.67	0.48		
Madagascar			2.92	0.47		
Mexico	1.19	0.31	1.86	0.12	3.80	1.25
Mali			2.31	1.10	3.91	0.53
Myanmar			1.78	0.40	4.23	0.91
Mozambique			3.15	0.12	4.17	0.52
Mauritania						
Mauritius						
Malawi			3.74	0.14	4.61	0.94
Malaysia			2.42	0.48		
Namibia						
Niger			2.47	0.00		
Nigeria			2.81	0.40	3.97	0.56
Nicaragua			2.34	0.54	4.23	0.49
Nepal	2.12	0.54	2.60	0.52	4.33	0.88
Oman						
Pakistan	1.19	0.86	1.37	0.56	4.13	1.02
Panama			2.40	0.68	3.19	0.67
Peru			1.28	0.31	3.72	1.36
Philippines			2.73	0.69	4.46	0.95
Palau						
Papua New Guinea						
Paraguay					3.96	0.55
Rwanda					5.42	0.92
Saudi Arabia	1.17	0.25				
Sudan						
Senegal			1.78	0.67	2.61	0.26
Singapore						
Solomon Islands						
Sierra Leone			2.75	0.24		
El Salvador					3.66	0.61
Somalia						

South Sudan						
Sao Tome and Principe						
Suriname			1.34	0.37		
Seychelles						
Chad					2.69	0.34
Togo			4.07	0.00	4.16	0.36
Thailand			2.45	0.64	2.19	0.35
Tonga						
Trinidad and Tobago						
Tanzania			4.21	0.45	4.16	0.88
Uganda			4.08	0.57	4.07	0.61
Uruguay	1.51	0.22	1.31	0.15		
Saint Vincent and the Grenadines						
Venezuela			1.18	0.27	2.54	1.18
Viet Nam			1.86	0.58	3.44	0.92
Vanuatu						
Samoa						
South Africa	1.41	0.40			3.63	1.09
Zambia					4.39	0.59
Zimbabwe					4.82	0.79

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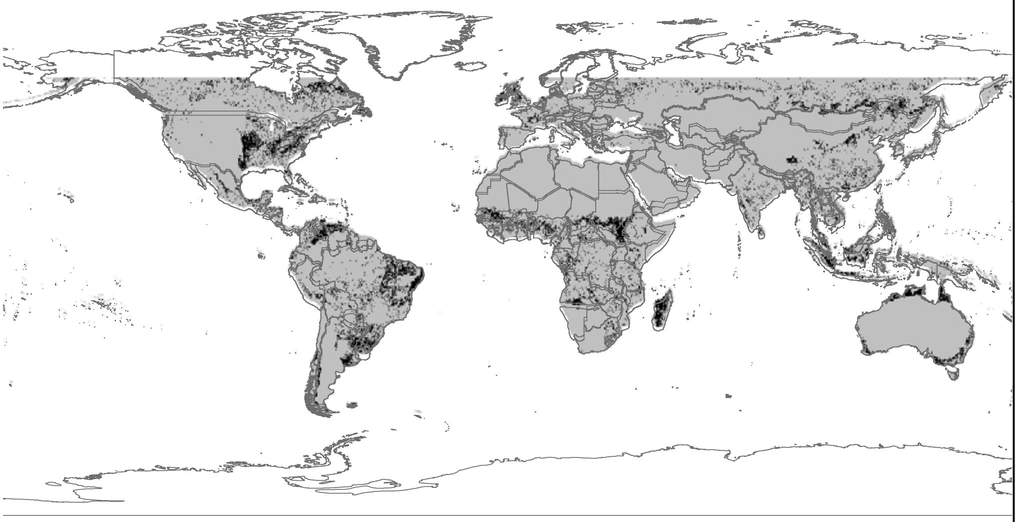

Figure S1. Available land (black) suitable for agricultural production between 60°N and 60°S calculated for this study.

Table ~~S2~~S3. Data appendix.

Country	Available land	Yield gap	Emissions gap (on agricultural land)	Forest loss due to agriculture (km² y⁻¹)	Source for forest loss calculations	REDD engagement
Angola	Medium	High	Low	254.09	FAO RSS (2000-2005) forest loss	0.14
United Arab Emirates	Low	No data	High	0.00	Hansen (2000-2012) forest loss	0.00
Argentina	High	Low	Low	3123.34	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.39
Antigua and Barbuda	Low	No data	High	No Data	No data	0.00
Burundi	Low	High	Medium	11.07	Hansen (2000-2012) forest loss	0.14
Benin	High	High	Medium	188.33	FAO RSS (2000-2005) forest loss	0.21
Burkina Faso	High	Medium	Medium	50.34	FAO RSS (2000-2005) forest loss	0.54
Bangladesh	High	Low	High	29.48	Hansen (2000-2012) forest loss	0.14
Bahamas	Medium	No data	Medium	4.32	Hansen (2000-2012) forest loss	0.00
Belize	Low	No data	Medium	97.79	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.18
Bolivia, Plurinational State of	Medium	Medium	Low	3649.01	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.63
Brazil	Medium	Medium	Medium	29470.29	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.54
Brunei Darussalam	Low	No data	High	23.05	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.00
Bhutan	Low	High	Medium	4.13	Hansen (2000-2012) forest loss	0.36
Botswana	Low	No data	Low	985.68	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.14
Central African Republic	Medium	High	Medium	720.89	FAO RSS (2000-2005) forest loss	0.43
Chile	Medium	Low	Medium	37.18	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.50
China	Medium	Low	Medium	6887.30	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.25
Côte d'Ivoire	High	High	Low	1321.29	FAO RSS (2000-2005) forest loss	0.46
Cameroon	Medium	High	Medium	3308.10	FAO FRA (2000-2010) net & FAO RSS (2000-	0.54

					2005) forest loss	
Congo, the Democratic Republic of the	Low	High	Low	2138.78	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.68
Congo	Medium	No data	Low	237.57	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.43
Colombia	Medium	Medium	Medium	795.99	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.64
Comoros	High	No data	Medium	0.55	Hansen (2000-2012) forest loss	0.00
Cape Verde	Low	No data	High	0.07	Hansen (2000-2012) forest loss	0.00
Costa Rica	Medium	Low	Medium	135.33	Hansen (2000-2012) forest loss	0.32
Cuba	High	Low	Medium	114.45	Hansen (2000-2012) forest loss	0.14
Djibouti	Low	No data	Low	0.00	Hansen (2000-2012) forest loss	0.00
Dominica	Low	No data	Medium	No Data	No data	0.00
Dominican Republic	Medium	Low	High	126.96	Hansen (2000-2012) forest loss	0.29
Algeria	Low	Low	Low	76.84	FAO RSS (2000-2005) forest loss	0.00
Ecuador	Medium	High	High	1231.85	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.43
Egypt	Low	Low	High	1.05	Hansen (2000-2012) forest loss	0.00
Eritrea	Low	No data	Low	0.00	Hansen (2000-2012) forest loss	0.00
Ethiopia	High	High	High	1892.59	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.36
Fiji	Low	No data	High	10.05	Hansen (2000-2012) forest loss	0.32
Micronesia, Federated States of	Low	No data	High	No Data	No data	0.00
Gabon	Low	No data	Low	108.36	FAO RSS (2000-2005) forest loss	0.46
Ghana	High	High	Low	877.04	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.64
Guinea	High	Medium	Low	543.84	FAO RSS (2000-2005) forest loss	0.00
Gambia	Medium	Low	High	0.77	Hansen (2000-2012) forest loss	0.00
Guinea-Bissau	Medium	Medium	Medium	119.35	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.14

Equatorial Guinea	Medium	No data	Low	44.73	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.25
Guatemala	Medium	High	Medium	551.90	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.46
Guyana	Low	Low	Medium	65.06	FAO RSS (2000-2005) forest loss	0.32
Honduras	Medium	High	Medium	477.53	FAO RSS (2000-2005) forest loss	0.25
Haiti	High	High	High	18.18	Hansen (2000-2012) forest loss	0.14
Indonesia	High	Medium	High	3490.95	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.96
India	Medium	Medium	High	885.89	FAO RSS (2000-2005) forest loss	0.25
Jamaica	Medium	No data	Medium	4.61	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.00
Kenya	High	High	Medium	750.36	FAO RSS (2000-2005) forest loss	0.57
Cambodia	Medium	Medium	High	892.78	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.54
Kiribati	Low	No data	Low	No Data	No data	0.00
Lao People's Democratic Republic	Medium	Medium	High	462.13	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.64
Liberia	Medium	High	Low	240.00	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.36
Libya	High	Low	Low	0.07	Hansen (2000-2012) forest loss	0.00
Saint Lucia	Medium	No data	High	No Data	No data	0.00
Sri Lanka	High	Medium	High	144.30	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.29
Madagascar	High	High	Low	673.03	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.43
Mexico	Medium	High	Medium	5780.33	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.71
Mali	High	High	Low	124.22	FAO RSS (2000-2005) forest loss	0.00
Myanmar	Medium	Medium	High	3347.05	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.07
Mozambique	Medium	High	Low	1285.02	FAO RSS (2000-2005) forest loss	0.39
Mauritania	High	No	Low	0.00	Hansen (2000-2012)	0.00

		data			forest loss	
Mauritius	High	No data	Medium	1.48	Hansen (2000-2012) forest loss	0.14
Malawi	Low	High	Low	102.38	FAO RSS (2000-2005) forest loss	0.29
Malaysia	High	Medium	High	925.89	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.25
Namibia	Medium	No data	Low	154.76	FAO RSS (2000-2005) forest loss	0.14
Niger	High	Medium	Low	0.00	Hansen (2000-2012) forest loss	0.00
Nigeria	High	High	Low	739.41	FAO RSS (2000-2005) forest loss	0.54
Nicaragua	High	High	Medium	700.00	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.36
Nepal	Low	High	High	208.24	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.43
Oman	Low	No data	Low	0.00	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.00
Pakistan	Low	Medium	High	5.14	Hansen (2000-2012) forest loss	0.36
Panama	Medium	High	Medium	59.00	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.54
Peru	Low	High	Medium	3652.49	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.86
Philippines	High	High	High	287.38	FAO RSS (2000-2005) forest loss	0.36
Palau	Medium	No data	Low	No Data	No data	0.00
Papua New Guinea	Medium	No data	High	2174.46	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.50
Paraguay	Medium	High	Medium	1796.45	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.52
Rwanda	Low	High	Medium	10.85	Hansen (2000-2012) forest loss	0.04
Saudi Arabia	Low	Medium	Low	0.00	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.00
Sudan	Low	No data	No data	0.58	Hansen (2000-2012) forest loss	0.21
Senegal	High	Medium	Medium	265.57	FAO RSS (2000-2005) forest loss	0.21
Singapore	High	No data	High	No Data	No data	0.14
Solomon Islands	Low	No data	Medium	33.96	Hansen (2000-2012) forest loss	0.14

Sierra Leone	High	High	Low	95.80	FAO RSS (2000-2005) forest loss	0.14
El Salvador	High	High	High	32.09	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.29
Somalia	Low	No data	Low	2.19	Hansen (2000-2012) forest loss	0.00
South Sudan	High	No data	No data	81.17	FAO RSS (2000-2005) forest loss	0.07
Sao Tome and Principe	Medium	No data	Low	No Data	No data	0.00
Suriname	Low	Medium	High	8.31	FAO RSS (2000-2005) forest loss	0.36
Seychelles	Low	No data	High	No Data	No data	0.14
Chad	High	High	Low	246.91	FAO RSS (2000-2005) forest loss	0.00
Togo	High	High	Low	180.10	FAO RSS (2000-2005) forest loss	0.14
Thailand	High	High	High	28.30	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.32
Tonga	Low	No data	High	No Data	No data	0.00
Trinidad and Tobago	Low	No data	High	8.14	FAO FRA (2000-2010) net & Hansen (2000-2012) forest loss	0.04
Tanzania, United Republic of	Medium	High	Medium	4145.80	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.50
Uganda	High	High	Medium	676.22	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.39
Uruguay	High	Medium	Medium	57.03	FAO FRA (2000-2010) net & FAO RSS (2000-2005) forest loss	0.18
Saint Vincent and the Grenadines	Low	No data	High	No Data	No data	0.00
Venezuela, Bolivarian Republic of	High	High	Medium	2416.33	FAO RSS (2000-2005) forest loss	0.18
Viet Nam	Medium	High	High	1303.22	FAO RSS (2000-2005) forest loss	0.50
Vanuatu	Low	No data	High	1.67	Hansen (2000-2012) forest loss	0.32
Samoa	Low	No data	High	No Data	No data	0.25
South Africa	High	High	Low	588.59	FAO RSS (2000-2005) forest loss	0.00
Zambia	Low	High	Low	2987.68	FAO RSS (2000-2005) forest loss	0.32
Zimbabwe	Medium	High	Low	2547.88	FAO FRA (2000-2010) net & FAO RSS (2000-	0.07

					2005) forest loss	