

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 could 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) are 4.3 GtCO₂e y⁻¹. 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. 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, with potential for forest-sparing interventions and a good enabling environment (e.g. effective governance or engagement in REDD+), there is a potential to

1 mitigate 1.3 GtCO₂e y⁻¹ (20 countries of 78 with sufficient data). For countries where we
2 identify agriculture emissions as a priority for mitigation, up to 1 GtCO₂e y⁻¹ could be reduced
3 from the agriculture sector including livestock. Risks to livelihoods from implementing
4 interventions based on national level data call for detailed investigation at the local level to
5 inform decisions on mitigation interventions. Three case-studies demonstrate the use of the
6 analytical framework. The inherent link between the agriculture and forestry sectors due to
7 competition for land suggests that these sectors cannot be considered independently. Our
8 findings highlight the need to include the forest *and* the agricultural sector in the decision
9 making process to mitigate deforestation.

10

11 **1. Introduction**

12 The agriculture and forestry sectors, including deforestation and forest degradation, are major
13 contributors of global greenhouse gas (GHG) emissions, accounting for approximately half of
14 low income countries' total GHG emission budgets (IPCC, 2014). Estimates suggest that
15 global emissions from deforestation were 4.9 ± 0.6 CO₂e yr⁻¹ in 2010, around 8% of
16 anthropogenic GHG emissions (Tubiello et al., 2015). According to Hosonuma *et al* (2012),
17 in 13 countries agricultural expansion is the only driver of deforestation. Natural vegetation is
18 at a higher risk than other land cover types, and a quarter is under threat from expansion of
19 agriculture (Creed et al., 2010). Between 1980 and 2000, 83% of agricultural expansion in the
20 tropics occurred in forested land causing major environmental impacts including loss of
21 carbon stocks and habitats (Gibbs et al., 2010). Agriculture itself has been an increasing
22 source of emissions, growing at around 1% annually since 1990 to 5.4 Gt CO₂e yr⁻¹ in 2012
23 (Tubiello et al., 2015).

24 Land-sparing interventions are supposed to increase the output on agricultural land reducing
25 the need to increase agricultural areas promoting deforestation (Stevenson et al., 2013).
26 Agricultural intensification which reduces the gap between potential yield and actual yield
27 (Byerlee et al., 2014; van Ittersum et al., 2013; Neumann et al., 2010; Wilkes et al., 2013) can
28 contribute to land sparing. The potential yield is the maximum yield given the biophysical
29 conditions – with the absence of any limitations (Neumann et al., 2010). The agricultural
30 yield gap can be reduced by interventions into the farming system for example by altering the
31 timing or method of applying agricultural inputs, or increasing cropping frequency.
32 Depending on the introduced change, the intervention will require one or a combination of an

1 increase in labour, capital, technology or a methodological change. Yield gap data provides
2 information on where feasible improvements can lead to increased production (Neumann et
3 al., 2010). The tropics, where yields are typically lower than in temperate regions (West et al.,
4 2010), are often characterized by a rather high yield gap.

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

10 These interventions can be potentially included in REDD+ strategies and when implemented
11 with climate smart agriculture (CSA) principles, can reduce emissions from agriculture as
12 well as avoiding deforestation (FAO, 2013). potential for community benefits to accompany
13 agricultural expansion and developments, however they can also negatively affect local
14 communities. Access to land can be compromised, and interventions may not offer equitable
15 distribution of benefits to stakeholders, excluding vulnerable communities (Mbow, 2010).

16 REDD+ is a results-based financing mechanism which funds activities to reduce emissions
17 from deforestation and forest degradation while promoting forest conservation, sustainable
18 management of forests and enhancing carbon stocks (UNFCCC, 2013). Interventions in the
19 agriculture sector, for example agroforestry, are considered promising options to reduce
20 emissions under REDD+ (Grieg-Gran, 2010), and by 2012, 42 national governments
21 considered agriculture in their REDD+ readiness strategies (Kissinger et al., 2012). However,
22 many countries do not establish REDD+ interventions which address the drivers of
23 deforestation, including agricultural expansion (Salvini et al., 2014).

24 To evaluate land-sparing interventions, our study systematically compares countries to show
25 which have the largest potential to mitigate GHG emissions from agriculture-driven
26 deforestation, and from agriculture (figure 1). Firstly, we quantify emissions from agriculture-
27 driven deforestation and agriculture in each country. Secondly, we pose the question whether
28 closing the yield gap and utilizing available land could be potentially incorporated into the
29 REDD+ context to address these emissions. In addition, we assess the potential for reducing
30 emissions directly from existing agricultural land using CSA. We indicate countries which are
31 likely to require increased support to implement mitigation initiatives by assessing their
32 capacity to implement interventions. Lastly, we assess risks to livelihoods from the

1 implementation of interventions. Mitigation pathways in three selected countries are explored
2 in depth to illustrate the applications of this framework and to demonstrate that decisions
3 made using the framework at the global level are relevant for the country level.

4 **2. Data and methodology**

5 This study considered all tropical (within the tropics, or with a tropical biome) (WWF, 2013)
6 non-annex 1 countries or countries who are engaged in REDD+. Not all had data available to
7 assess the mitigation potential (figure 1), leaving 78 countries which represent 85 % of the
8 forest area in the tropics for the study. However, 97 countries had data available to calculate
9 emissions from agriculture-driven deforestation and of those, all but two had data on
10 emissions from agriculture (n=95 for total emissions), so these results are presented (section
11 3.1).

12 We developed a framework to assess the current potential of each country to mitigate GHG
13 emissions from agriculture-driven deforestation and agricultural activities (figure 2). We
14 looked at the potential for mitigation through sparing land by (1) closing the yield gap and (2)
15 by utilising non-forested land suitable for agricultural activities. It is possible that synergies
16 occur between closing the yield gap and utilizing available land that can provide benefits
17 when both mitigation approaches are implemented within the same country. However, in this
18 study we assume there is potential to mitigate agriculture-driven deforestation when either
19 one of the two approaches is feasible, and we do not consider any additional mitigation
20 benefits in countries with potential for both approaches. Where agricultural emissions are
21 largest, we estimated the potential to mitigate these emissions. For countries with a high
22 potential for mitigation, we assessed the potential for a mitigation intervention to be
23 implemented successfully, by considering constraints to effective implementation (poor
24 governance, lack of engagement in REDD+). Risks to livelihoods as a result of interventions
25 (indicated by food insecurity) were then considered. Countries were divided into three groups
26 using each data source, and groups were defined by dividing the data at the 1/3rd and 2/3rd
27 percentiles. Percentiles were calculated accounting for all the countries with available data for
28 that data source within the tropics (Table 1).

2.1. Calculation of emissions

The source of emissions was 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 estimated total deforestation areas 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 China, India and Vietnam, large-scale afforestation projects will lead to an underestimation of 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; the Forest Resources Assessment Remote Sensing Survey (FRA RSS) is sample data which does not cover the whole of the tropics. Therefore, we combined 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’ (Fig. 3). We used this factor to estimate 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 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 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

1 et al., 2012). Romijn *et al* (2012) evaluated the existing monitoring capacities of countries
2 taking into consideration challenges such as the area of forest which the country has to
3 monitor and availability of data.

4 Where the conditions described above were not met, and Eq. 1 is therefore unsuitable, we
5 selected first the FRA RSS alone to provide the loss, and if this did not meet the error criteria
6 based on the number of samples, we used the Hansen data alone, where it was available.
7 Otherwise we recorded no-data (no data was also recorded where only FAO FRA net change
8 is available). Data are available for most of the tropics, and the 12 no-data countries (out of
9 109 countries) account for only 0.02% of forest area considered in this study. For the majority
10 of the data (countries which hold more than 69% of forest in the tropics), loss was calculated
11 using FAO FRA in combination with either FRA RSS or Hansen (Fig. 3).

12 For future projections of deforestation areas, a historical baseline period which is sufficiently
13 long to compensate for any anomalous high and low years is required (Santilli et al., 2005).
14 Here, we considered a period of 10 years, which is in line with other studies (e.g. Rideout *et*
15 *al* 2013).

16 **2.1.2. Area of forest loss due to agriculture**

17 Based on the national total area of deforestation we calculated the area that was deforested
18 due to agriculture. In this study, we used the definition of deforestation drivers used by
19 Hosonuma et al. (2012) and Kissinger et al. (2012). Drivers can be separated into direct and
20 indirect drivers. Since the definition for deforestation considers a change in land use, timber
21 extraction is not considered as a driver, as the forest is expected to regrow. Direct drivers
22 relate to an intended land use (for example, urban expansion, mining, agriculture and
23 infrastructure). Indirect drivers include international markets and population growth that
24 influence the land change. We used national data from Hosonuma et al. (2012) describing the
25 importance of agriculture as a direct driver of deforestation. Agriculture includes cropland,
26 pasture, tree plantations, and subsistence agriculture including shifting cultivation (Hosonuma
27 et al., 2012). The authors derived the importance of deforestation drivers from a synthesis of
28 nationally self-reported data, country profile reports from the Center for International Forestry
29 Research (CIFOR) and other literature, most of them reflecting the timeframe between 2000
30 and 2010. The relative importance of the drivers mentioned in the reports is quantified either
31 as a ratio, ordinal, or nominal scale. These were scaled from 0 to 1 (representing minimal to

1 high influence), to indicate the proportion of deforestation which is driven by agriculture (see
2 Hosonuma et al. 2012 for details). We multiplied this ‘agricultural driver factor’ by the area
3 of forest loss ‘deforestation’ to infer the area of loss driven by the agriculture: ‘agriculture-
4 driven deforestation’ (Eq. 2).

$$5 \text{ Agriculture driven deforestation} = \text{deforestation} * \text{agricultural driver factor} \text{ (2)}$$

6 According to the method used in Harris et al. (2012), we calculated emissions by multiplying
7 the area of forest loss by an emissions factor. For the biomass emissions factor, we use the
8 sum of above ground biomass (AGB) and below ground biomass (BGB). We averaged two
9 AGB datasets derived from remote sensing and ground measurements; a tropical dataset
10 (Saatchi et al., 2011) and, a continental dataset (Baccini et al., 2012). Using an average of the
11 two maps is preferred (where there is coverage from both datasets), since the accuracy of both
12 approaches is yet to be determined (Zolkos et al., 2013). Where only one map has data, we
13 used the dataset available. The mean AGB in each country was calculated in forested areas,
14 which were selected using the ESA Global Land Cover map of 2010 developed in the Climate
15 Change Initiative (CCI) (ESA, 2013). BGB was calculated from AGB using tree root to shoot
16 ratios equations (Mokany et al., 2006).

17 **2.1.3. Emissions from agriculture**

18 We used national emission data from FAO (2012) to calculate total emissions from
19 agriculture, covering enteric fermentation, manure management, rice cultivation, synthetic
20 fertilizers, manure applied to soils, manure left on pasture, crop residues, cultivation of
21 organic soils, burning – savanna, burning – crop residues and agricultural soils. We do not
22 account for sinks such as those which occur from crop re-growth. We excluded energy use in
23 agriculture. According to FAO (FAO, 2014a) agriculture includes livestock, and agricultural
24 land is defined as fallow land, temporary crops, temporary meadows for mowing and pasture,
25 permanent crops and permanent meadows and pasture.

26 **2.2. Mitigation potential**

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

1 potential as the total mitigation which could be achieved over time. We do not consider
2 practical constraints (technical potential), or cost limitations (economic potential) (Baede et
3 al., 2007).

4 **2.2.1. Closing the yield gap**

5 Production of maize, wheat and rice provides about two-thirds of all energy in human diets
6 (Cassman, 1999) and therefore, we focus on these three crop types in our analysis. First, we
7 calculated the average yield gap of these three cereals for each country based on Neumann et
8 al. (2010). Second, we derived the crop-specific production area per country based on
9 Monfreda et al. (2008). In our study, the yield gap at national level is calculated by the
10 following function (Eq. 3), using yield gaps and production areas of each crop (x).

$$11 \text{cereal yield gap} = \sum \frac{\text{mean yield gap } x}{\text{total cereal area}} * \text{cereal area } x \quad (3)$$

12 **2.2.2. Non-forested land suitable for agriculture**

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

20 **2.2.3. Potential for reduction of agricultural emissions**

21 Where the majority of emissions are in the agriculture sector (Fig. 1), we calculated the
22 emissions t CO₂e per hectare of agricultural land using national emissions data (section 2.1.3),
23 and agricultural area data (FAO, 2014b). High emissions shows that there are emissions
24 which could potentially be reduced.

25 **2.3. Enabling environment**

26 To represent the enabling environment for mitigating deforestation we used two indicators:
27 governance and engagement in REDD+. To indicate governance, we summed the following

1 components of a governance index, available from the World Bank (2012): government
2 effectiveness, regulatory quality, rule of law and control of corruption.

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

24 **2.4. Risk assessment**

25 We assessed the risk to livelihoods potentially resulting from the implementation of the
26 mitigation interventions. Risk is dependent on many elements, which can be grouped into
27 three components: hazard (physical realization of the risk), exposure (elements exposed to the
28 risk) and vulnerability (susceptibilities of the exposed elements) (Cardona et al., 2012). We
29 consider that the hazard (a system change leading to changes to land use) occurs, and that the
30 exposed elements are local communities. We then use a food security index as a proxy for
31 vulnerability, reflecting risk as a whole (<http://foodsecurityindex.eiu.com/>).

1 **3. Results**

2 **3.1. Sources of emissions**

3 In the tropics, a total of 104,260 km² yr⁻¹ of forest on average was lost between 2000 and
4 2010/12 (dependent on data input; see Fig. 3) to agriculture (97 countries), which resulted in
5 4.26 GtCO₂ y⁻¹ emitted to the atmosphere (Fig 4.). The largest forest loss due to agriculture
6 occurred in Brazil (29,470 km² y⁻¹). On average, countries lost 0.52% yr⁻¹ of their forest to
7 agriculture, with the highest percent loss in Togo (3.71% y⁻¹).

8 The emissions are categorized as follows (Table 1): (1) agriculture-driven deforestation
9 emissions are the main source of the total emissions (>66%); (2) agricultural emissions are the
10 main source of the total emissions (>66%) and (3) agriculture-driven deforestation and
11 agriculture each contribute 33-66% to the total emissions. Those countries where emissions
12 from deforestation are highest include those which have high forest losses due to agricultural
13 expansion, e.g., Zimbabwe 1.35% yr⁻¹ (2548 km² y⁻¹), and those with a large forest area, e.g.,
14 Brazil which loses 0.54% yr⁻¹ (Figs. 4 and 5). Some countries with high agricultural emissions
15 have no deforestation due to agriculture (United Arab Emirates, Djibouti, Eritrea, Mauritania,
16 Niger, Oman, Saudi Arabia). Haiti is an exception which has a high forest loss due to
17 agriculture (>2% y⁻¹) but most emissions are from the agricultural sector due to the small
18 forest area remaining (1090 km² in 2000, ~4% of the country area).

19 **3.2. Mitigation potential of agriculture-driven deforestation**

20 In total, 78 countries were classified according to their mitigation potential using the decision
21 tree (Fig. 2); the main results are presented in Table 4. Out of 44 countries with >33% of the
22 total emissions from agriculture-driven deforestation, 33 countries also have either a high
23 yield gap or a large area of available land compared to forest land (Table 4). Available land is
24 highest in South East Asia and West Africa (Fig. 6). The yield gap is highest in East and
25 Central Africa and Central America with the yield gap being already closed in much of Asia
26 and South America (Fig. 6). Of those countries with a high yield gap or large area of available
27 land 20 countries have a good enabling environment in terms of effective governance or
28 engagement in REDD+. These countries have a mitigation potential of 1.32 Gt CO₂ y⁻¹ from
29 reducing agriculture-driven deforestation. Most countries in Asia and South and Central
30 America have strong enabling environments for interventions, with either effective
31 governance or involvement in REDD+ (Fig. 6). Central Africa has high engagement in

1 REDD+ and some countries in Southern Africa have a high governance scores. Sub-Saharan
2 Africa has the weakest enabling environment for mitigation interventions. Food insecurity
3 indicates a risk to livelihoods when implementing mitigation interventions, and 14 out of the
4 remaining 20 countries have high risks (Table 3). Six priority countries have been identified,
5 which have potential to mitigate agriculture-driven deforestation, and also have a good
6 enabling environment and low risks associated with implementing an intervention: Panama,
7 Paraguay, Ecuador, Mexico, Malaysia and Peru (Table 4).

8 **3.3. Mitigation potential of agricultural emissions**

9 Thirty-eight countries with either >66% of total emissions from agriculture or 33-66% of total
10 emissions from agriculture and no mitigation potential through land-sparing (Fig. 2) were
11 assessed for the potential to mitigate emissions from agriculture. Of those 38 countries, 12
12 have a potential to mitigate up to 1 GtCO₂e y⁻¹ of agricultural emissions. However, only two
13 countries have a good enabling environment, and of those only Thailand has low risks
14 associated with the implementation of interventions, so mitigation potential is low.

15 **3.4. Priority areas for increased support**

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

1 **4. Discussion**

2 **4.1. The potential for mitigation of emissions from agriculture-driven** 3 **deforestation and agriculture**

4 Our results quantify annual forest losses which are driven by agriculture. Converting forest
5 loss to emissions, and comparing this to emissions from agriculture allows mitigation
6 approaches for the main source to be considered. We consider emissions to indicate the need
7 for mitigation rather than forest area loss, which gives a focus on countries with high carbon
8 forests. This can lead to valuable wooded ecosystems being neglected (Mbow, 2014).
9 However, countries with low carbon forests do appear in our study and are highlighted as
10 priorities for action (e.g. Zambia, Togo).

11 Following this, we consider the enabling environment and risks to identify priority countries.
12 This assessment can be used as a starting point for national priority setting and policy
13 processes. However countries with a low potential for mitigation should also be assessed at
14 the sub-national level for opportunities. In addition, risks should be assessed at the local level
15 and even where low risks are identified, activities should be accompanied by safeguards that
16 ensure that the rights and livelihoods of local communities and biodiversity are respected
17 (Peskett and Todd, 2013). REDD+ interventions can potentially bring benefits to
18 communities, but can also bring negative impacts resulting from restrictions on access to
19 forests, changes to permitted land management practices (Peskett and Todd, 2013), or altered
20 agricultural practices (Smith et al., 2013). The likelihood that negative impacts will result is
21 dependent on the safeguarding systems implemented with the intervention (Peskett and Todd,
22 2013).

23 We explored three national case studies in more detail, providing recommendations for the
24 mitigation of emissions from both agriculture-driven deforestation and from agriculture
25 (Table 5). Two cases represent the potential to mitigate deforestation related emissions
26 (Democratic Republic of Congo (DR Congo) and Indonesia), and one case study highlights
27 the case for targeted interventions within the agricultural sector (Argentina). All countries
28 have emissions $>1 \text{ Gt CO}_2\text{e yr}^{-1}$ (Fig. 2), and have supporting data available to evaluate the
29 use of the framework for the assessment of the mitigation potential.

1 **4.1.1. Case study: DR Congo**

2 Emissions from agriculture-driven deforestation in the DR Congo account for 98% of the total
3 emissions (emissions from agriculture plus agriculture-driven deforestation). There is a strong
4 consensus that the major direct driver of deforestation in DR Congo is agriculture, and due to
5 increasing populations and weak governance, deforestation rates are likely to increase in the
6 future (Ickowitz et al., 2015). A high mitigation potential exists to reduce agriculture-driven
7 deforestation given the high yield gap, although available land is rated low (~12%). Reports
8 suggest that one of the major barriers to the implementation of interventions in agriculture is
9 the lack of transport infrastructure and access to markets (Ickowitz et al., 2015). However,
10 engagement in REDD+ is high, suggesting a strong enabling environment for land-use related
11 interventions. Vulnerable communities may be affected by land based activities, since DR
12 Congo is food insecure. Roots, tubers and plantains comprise more than the half of the dietary
13 requirements in the DR Congo and a fall in production over recent years has led to fall in the
14 average caloric intake (Alexandratos and Bruinsma, 2012). Together with the country's state
15 of post-conflict recovery this suggests that food insecurity will remain in the near future.

16 **4.1.2. Case study: Indonesia**

17 In Indonesia 41% of the total agriculture and agriculture-driven deforestation emissions
18 originate from agriculture. Since Indonesia has available land approximately half the area of
19 its forests and a relatively small yield gap (2.22 t h^{-1}), the identification of unused land could
20 be explored as a priority. Caution should be taken since the conversion of Indonesia's high
21 carbon peat swamps to can lead to a large flux of emissions – in the case of oil palm this is a
22 change from a net of -1.3 to $30.4 \text{ Mg CO}_2\text{e ha}^{-1} \text{ y}^{-1}$ (Hergoualc'h and Verchot, 2013).
23 Amongst all countries included in our analysis Indonesia has the highest engagement in
24 REDD+, and has already implemented national policy interventions designed to protect
25 forests from conversion to agriculture, such as a moratorium on forest conversion (Angelsen
26 et al., 2012). However Indonesia is a major producer of oil palm and this has led to an
27 expansion of agricultural land (Alexandratos and Bruinsma, 2012) so coordination from the
28 agriculture and forestry sectors is required where there is competition for land. In terms of
29 risks, Indonesia faces some food insecurity, so this should be considered and monitored to
30 ensure that unwanted trade-offs do not result from interventions.

1 **4.1.3. Case study: Argentina**

2 In Argentina, 73% of the total emissions from agriculture-driven deforestation and
3 agriculture, originate from agriculture. Argentina has the 8th highest (average 1990-2011)
4 agriculture emissions in the world – largely resulting from livestock keeping (FAO, 2014b),
5 and it is expected that these emissions will continue to rise due to increasing beef demand, so
6 advances in the livestock sector need to be explored for assessing the potential for emissions
7 reductions. In terms of addressing the proportion of emissions in Argentina occurring from
8 agriculture-driven deforestation, there is a large area of available land (our study predicts that
9 this is around 122% of the forest area) so there is a potential to avoid deforestation.
10 Successful interventions such as a tax on soybean exports (Kissinger et al., 2012), which are
11 driving land acquisitions (www.landmatrix.org) have also contributed to reduced expansion of
12 agriculture land. Although our study finds a relatively low yield gap (1.78 t ha⁻¹) there is still
13 room to narrow, so land-sparing could potentially occur from an intervention targeting the
14 yield gap. Governance is medium in Argentina (-0.35) so interventions are likely to be
15 successful, although some capacity building could be integrated into interventions in the short
16 term, since Argentina's R-PP states that insufficient law enforcement is one of the indirect
17 drivers of deforestation (Kissinger et al., 2012).

18 **4.2. Calculating emissions from deforestation**

19 A number of studies have calculated emissions from recent deforestation. Achard et al. (2014)
20 use the FRA RSS sample data (see section 2.1.1) and find emissions between 2.2 and 4.3 Gt
21 CO₂ yr⁻¹ between 2000 and 2010. We find emissions of 5.14 Gt CO₂ yr⁻¹ for the tropics,
22 which are 13% higher than Achard et al. (2014). For 73 tropical countries (excluding the
23 Caribbean), Harris et al. (2012) finds emissions of 1.9 - 4.73 Gt CO₂ yr⁻¹ between 2000 and
24 2005 from deforestation. Our estimate for the same 73 countries is 4.83 Gt CO₂ yr⁻¹, 2%
25 above the upper limit for Harris et al. (2012). Although our results are higher than these
26 estimates, Harris' estimates are typically lower than other recent estimates (Harris et al.,
27 2012), which supports our findings. In terms of the area of deforestation, Harris et al. (2012)
28 find annual forest loss for 73 tropical countries (excluding the Caribbean) of 36,750 - 143,330
29 km² y⁻¹ (with a median of 85,160). This supports our results for the same countries (we
30 estimate 117,486 km² y⁻¹ total forest loss not only driven by agriculture), which lies within the
31 same range. Estimates of deforestation area from Achard et al. (2014) are not easily

1 comparable to estimates based on country reported data (including our study) and disagree
2 with the FAO FRA data partly due to the definition of forests (Achard et al., 2014). The major
3 difference between estimates stems from the emissions factors rather than the activity data.
4 Since our study uses a comparative approach to assess the need for mitigation on a country
5 level, we consider these data still useful for this purpose. Emissions from deforestation can
6 also be higher than we predict, as these studies do not consider losses from peat soils, burning
7 of the forest or other GHGs.

8 **4.3. Projecting agriculture-driven deforestation**

9 Estimates of the mitigation potential of reducing agriculture-driven deforestation are
10 inherently reliant on future estimates of agriculture-driven deforestation. These projections
11 rely on assumptions about the future, and baseline setting which is one of the challenges of
12 REDD+ (Köthke et al., 2014). Historical deforestation rates are commonly used for setting
13 business-as-usual (BAU) baselines for avoided deforestation (Santilli et al., 2005). We
14 therefore selected this approach for our study, however other approaches may lead to more
15 reasonable estimates. For example, adjusting historic baselines based on the forest transition
16 curve (FT) to make projections can be beneficial since otherwise countries at the early stages
17 of the transition will underestimate future BAU deforestation and countries at later stages of
18 the transition will overestimate BAU (Angelsen, 2008; Köthke et al., 2014). However, future
19 scenarios should also account for global economic forces and government policies which are
20 not accounted for in the FT, and there are a number of countries which do not fit into the
21 typical FT trajectory, for example Thailand (Meyfroidt and Lambin, 2011). Simulation
22 models are often used to estimate deforestation based on relationships between deforestation
23 and variables such as population, and have been used for a number of applications
24 (Kaimowitz and Angelsen, 1998). Global models are useful for estimating deforestation since
25 they account for leakage across national borders, and partial equilibrium models (e.g.
26 GLOBIOM) are able to model competition for land by accounting for multiple sectors, e.g.
27 agriculture, forestry and bioenergy. However, there is not always a clear relationship between
28 deforestation and the selected explanatory variables, and some aspects of human behaviour
29 such as social and political changes are impossible to predict, consequently leading to
30 projections with high uncertainties (Dalla-Nora et al., 2014; Kaimowitz and Angelsen, 1998).
31 In addition, there is some scepticism on models which are based on assumptions about
32 economic behaviour, and those models which are based on household data are considered

1 most reliable, which are only useful for local level estimates (Kaimowitz and Angelsen,
2 1998).

3 **4.4. Estimating available land**

4 Land available for agriculture is one of the indicators for the potential to mitigate agricultural
5 expansion into forests. However, there are many difficulties in quantifying available land
6 (Lambin et al., 2013). There are several limitations to our the approach including: (1) the rain-
7 fed potential productivity is considered, which can be exceeded by irrigation, (2) the applied
8 threshold for the minimum potential productivity of 3.5 t ha⁻¹ can be considered overly
9 conservative, since many areas are cultivated with lower production levels (Droogers et al.,
10 2001), (3) suitability for agriculture is crop specific, so it is possible that there are some crop
11 types which can potentially produce above 3.5 t ha⁻¹ in the ‘very-low productivity’ areas, (4)
12 it is a static approach which does not take into account likely impacts of future climate change
13 on crop production (Frieler et al., 2015; Rosenzweig et al., 2014), (5) the land cover classes
14 used in the availability criteria imply availability, but can also include some land already in
15 use (6) we excluded slopes above 15%, which can, however, potentially be cultivated using
16 terracing. The 15% slope threshold however, is commonly used to identify agricultural
17 suitability at large scale since this is the threshold where the kinetic energy of the runoff
18 increases and outweighs the kinetic energy of the rainfall thus resulting in erosion (Roos,
19 1996). Regarding the implied land availability, we acknowledge that some areas may not be
20 available, for example grazed areas may not be in the agriculture land cover class of the land
21 cover dataset. Promoting agriculture expansion in areas which are used by local communities
22 can lead to negative effects (Mbow, 2010). Yet, land availability was used to indicate the
23 amount of available land rather than identifying areas for agricultural development, which
24 requires local evaluation including risk assessments. Despite its limitations, comparisons with
25 other datasets support our approach. Within the tropics we find approximately 8,290,000 km²
26 of available land (Fig. 1S in the supplement). This is over 11% of the total terrestrial area.
27 Other studies also suggest that there are large areas of land available globally for example
28 Campbell et al. (2008) finds that over 3.5% of the land area is suitable for bioenergy
29 production when only considering abandoned agricultural land. Lambin et al. (2013)
30 calculated available land, and we compared three areas for which data are available with our
31 own study, and they are within the same range (Table 6). Lambin et al. (2013) used a bottom-
32 up approach to estimate the world’s potentially available cropland based on a series of

1 constraints and trade-offs which are considered in different scenarios. A global figure of
2 13,220,000 km² was calculated using comparable processes, which is also within the same
3 order of magnitude as our findings (Fader et al., 2013).

4 **4.5. The land-sparing hypothesis**

5 To spare land the yield gap needs to be sufficiently decreased or even closed, and available
6 land needs to be successfully used. The extent to which the yield gap can be closed in practice
7 depends on location-specific technological, biophysical and other constraints (Duwayri et al.,
8 2000; Neumann et al., 2010). It is widely recognised that technological advances in
9 agriculture, which improve production can reduce the need to expand agricultural production
10 into forests (Borlaug, 2007; Stevenson et al., 2013). Yield gaps vary within countries (Table.
11 2S, in the supplement), and areas where yield gaps are highest may be targeted for
12 interventions. Scenarios suggest that a 1% crop yield increase annually would spare 0.76
13 billion ha of cropland expansion by 2050 (Sands and Leimbach, 2003). Despite increases in
14 fertilizer use, higher yields can reduce emissions, due to a reduced emissions intensity from
15 production (Burney et al., 2010). In order to avoid social and environmental costs of
16 agricultural intensification, including increased emissions, ‘climate smart’ or ‘sustainable
17 intensification’ principles can be followed (Foley et al., 2011; Garnett, 2012). This theory,
18 however, has been much debated recently, with some research finding that any savings will be
19 offset by changing human diets and increased population (Bajzelj et al., 2014; Kastner et al.,
20 2012).

21 Few examples are cited in the literature where intensification or utilization of available land
22 has led to land-sparing (Cohn et al., 2011; Minang et al., 2011; Stevenson et al., 2013),
23 perhaps since few programmes are developed with this aim. However, in the case of Brazil,
24 Nationally Appropriate Mitigation Actions (NAMAs) to restore grazing land account for 10-
25 12 % (0.1-0.13 Gt CO₂) of pledged emission reductions for the year 2020 (Cohn et al., 2011).
26 Despite the potential for emissions reductions from utilizing available land, there will always
27 be emissions created from the utilization of these lands (Searchinger et al., 2015). However,
28 when weighted against potential deforestation emissions, the carbon balance can be tipped in
29 favour of conversion of available lands. In addition, where available lands are degraded (one
30 of the reasons land is not currently utilized), rehabilitating them can increase the carbon
31 storage capacity of soils, so adding to the mitigation potential (Smith et al., 2008).

1 Even if the yield gap has been closed, and available land utilized, land-sparing must become a
2 reality in order for deforestation to be reduced. Some studies suggest that feedbacks such as
3 increasing land rents from yield improvements will lead to increases in land area dedicated to
4 agriculture (Angelsen, 2010). Intensified production has been found more likely than
5 smallholder production to expand into forests (Gutiérrez-Vélez et al., 2011) and freeing
6 grazing lands can lead to more demand for cropland to supply feed for the livestock
7 (Cattaneo, 2001). However, we consider the level of governance as a criterion in the selection
8 of areas for interventions which will support the integration of policies to limit agricultural
9 expansion such as LSPs (Cohn et al., 2011; Rudel et al., 2009). Governance indicators, such
10 as rule of law and control of corruption (World Bank, 2012) are related to the effective set-up
11 and management of interventions and accompanying policies, and have been used as an
12 indicator of the enabling environment for interventions. The state of Mato Grosso in Brazil is
13 one example where agriculture-driven deforestation has been reduced by the integration of
14 policies including the soybean industry's self-imposed moratorium (2006) on production in
15 deforested areas and pro-active efforts by the local and national governments to control
16 deforestation (DeFries et al., 2013). Although national level governance may be good, central
17 governments may not support community level actions, so a multilevel system is important
18 (Angelsen, 2010). NAMAs can also help to achieve targets of agricultural mitigation, can help
19 to reduce leakage risks and foster wider engagement at the country level, and can be
20 combined within REDD+ mechanisms (Kissinger et al., 2012).

21 **5. Conclusions**

22 This study gives a comprehensive overview of national emissions and mitigation priorities
23 within the forest and agriculture sectors, which can guide decision making and investments at
24 the international level. Specifically, we have demonstrated how available data can be used to
25 identify where emissions from agriculture, forestry and other land use (AFOLU) sector within
26 the IPCC reporting scheme can be best reduced. The inherent link between agriculture and
27 forests highlights need for integrated solutions. Agricultural interventions have been
28 incorporated into REDD+ frameworks in some countries, including Indonesia and Brazil
29 (Kissinger et al., 2012). Yet, there is potential for improvement to ensure that where
30 agricultural drivers are present, those are addressed with appropriate interventions within the
31 agricultural sector (Salvini et al., 2014). This task is not without difficulties, since government
32 agencies focussing on agriculture and those focusing on forestry may have differing

1 objectives, and a systematic incorporation of policies is required to consider competing goals.
2 In addition, if interventions are implemented in the agricultural sector to spare forest land,
3 then support from the forestry sector is also necessary to protect existing forests.

4 Our findings show a mitigation potential of 4.26 GtCO₂e y⁻¹ from agriculture-driven
5 deforestation. Many countries also have a high potential to implement successful
6 interventions in the agricultural sector, as there is a good enabling environment (effective
7 governance or engagement in REDD+) which will support activities. A potential of 1.32
8 GtCO₂ y⁻¹ can be mitigated in those countries in which more than one third of their emissions
9 stem from agriculture-driven deforestation and which have a good enabling environment (20
10 countries). These countries are responsible for 31% of the total emissions from agriculture-
11 driven deforestation in the tropics. They potentially hold the easiest gains and interventions
12 which seek to spare forest land by decreasing the yield gap, or by expanding agriculture into
13 available non-forest lands and these opportunities should be systematically considered. Some
14 of these countries have risks (e.g. Indonesia and DR Congo) associated with potential
15 mitigation interventions and this should be considered as part of the decision making process.
16 A number of countries have a high mitigation potential but indicators for these countries
17 suggest a weak enabling environment (e.g. Angola, Honduras) (table 4). In these cases, long-
18 term support which also seeks to build governance capabilities is required.

19 Within the agriculture and forestry sectors in particular, there are potential trade-offs (risks to
20 livelihoods) associated with mitigation interventions. These interventions carry potential
21 social and environmental costs and following the principles of ‘sustainable intensification’ or
22 ‘climate-smart’ agriculture can minimize these costs (Foley et al., 2011; Garnett et al., 2013).
23 Interventions which deliver multiple benefits, in terms of yield increases, mitigation and
24 adaptation components can also offer opportunities to support vulnerable communities where
25 risks such as food insecurity or reliance on agriculture for income are present. There is a need
26 to look beyond the broad interventions which are discussed in this paper, and the growing
27 body of evidence on climate-smart agriculture (FAO, 2013) is providing examples of best
28 practices in specific locations. Further research is also required to consider other risks, for
29 example to biodiversity, which can be impacted by changes to agricultural systems. This
30 systematic framework can be replicated for other scenarios, or at other scales (for example
31 regional and local) to identify priorities for mitigation across sectors in a transparent manner.

32 **Author contributions**

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

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- 35

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

Decision step		Categories		
Emissions assessment		Agriculture	Deforestation	Both
Total emissions (tCO ₂ e)	Emissions (CO ₂) which come from agriculture-driven deforestation (multiple data sources - see section 2.2) and from agriculture (CH ₄ , N ₂ O, CO ₂) (Emissions from agriculture 2010 [or most recent data point available] [t CO ₂ e] ¹ (FAO, 2014b))	>66% is	>66% is	33-66% is
		emissions from agriculture-driven deforestation	emissions from agriculture-driven deforestation	emissions from agriculture-driven deforestation and agriculture
Mitigation potential		Low	Medium	High
Yield gap (t ha ⁻¹)	Area weighted yield gap of major grains (Neumann et al., 2010) based on the area under production (Monfreda et al., 2008).	<2.21	2.21-3.6	>3.6
Available land (%)	Area of non-forested, non-protected, unused land, with minor slopes <15% and a potential for >3.5 t ha ⁻¹ agricultural production. Expressed as a percentage of forested land (multiple data sources – see table 2).	<17	17-44	>44
Agricultural emissions (t CO ₂ e ha ⁻¹)	Emissions (CH ₄ , N ₂ O, 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 >51 (http://foodsecurityindex.eiu.com/)	34-51	<34
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1 ¹ CO_{2e} – equivalent concentrations of other GHGs in terms of radiative forcing as carbon
2 dioxide.

3
4 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

5

6 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)

7

8 Table 4. Countries are categorized into mitigation intervention classes according to the results
9 of the decision making tree (Fig. 1) which identifies target countries for mitigation
10 interventions using thresholds for input data (table 1). Priority countries (with low risks) for

- 1 interventions are emboldened (countries for which data are unavailable for the full analysis
- 2 are not included).

<i>Contribution of emissions to total</i>	<i>Agriculture >66%</i>	<i>Agriculture and agricultural driven deforestation emissions 33-66%</i>		<i>Agricultural driven deforestation >66%</i>
<i>Potential for mitigation (sector)</i>	<i>Agriculture</i>	<i>Agriculture</i>	<i>Forest</i>	<i>Forest</i>
<i>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)</i>	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
<i>High potential but support for governance required (countries are not assessed for risk)</i>	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
<i>Low potential (countries are not assessed for governance or risk)</i>	Argentina Burundi Burkina Faso Chile China Comoros Cuba Djibouti Algeria	Colombia Guinea-Bissau		Bolivia, Brazil Costa Rica Guyana Cambodia Lao PDR Myanmar

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

1

2 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

3

4 Table 6. Available land area (in '000 km²) for three regions

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

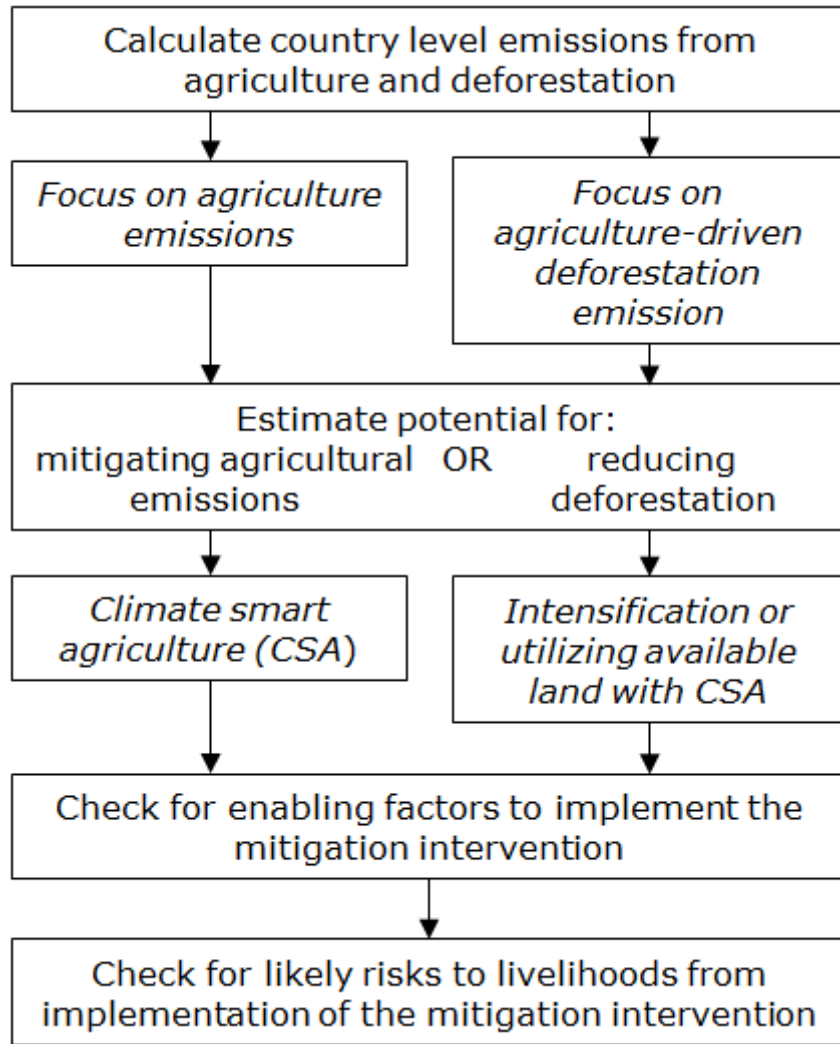
1 *The Brazilian and Bolivian Amazon region consists of Bolivia, and 5 states in Brazil;
2 Maranhão, Pará, Mato Grosso, Rondônia, and Acre (the Lambin et al. (2013) area is slightly
3 smaller, as it only considers Pará south of the Amazon River, which is the ‘Amazon arc of
4 deforestation’).

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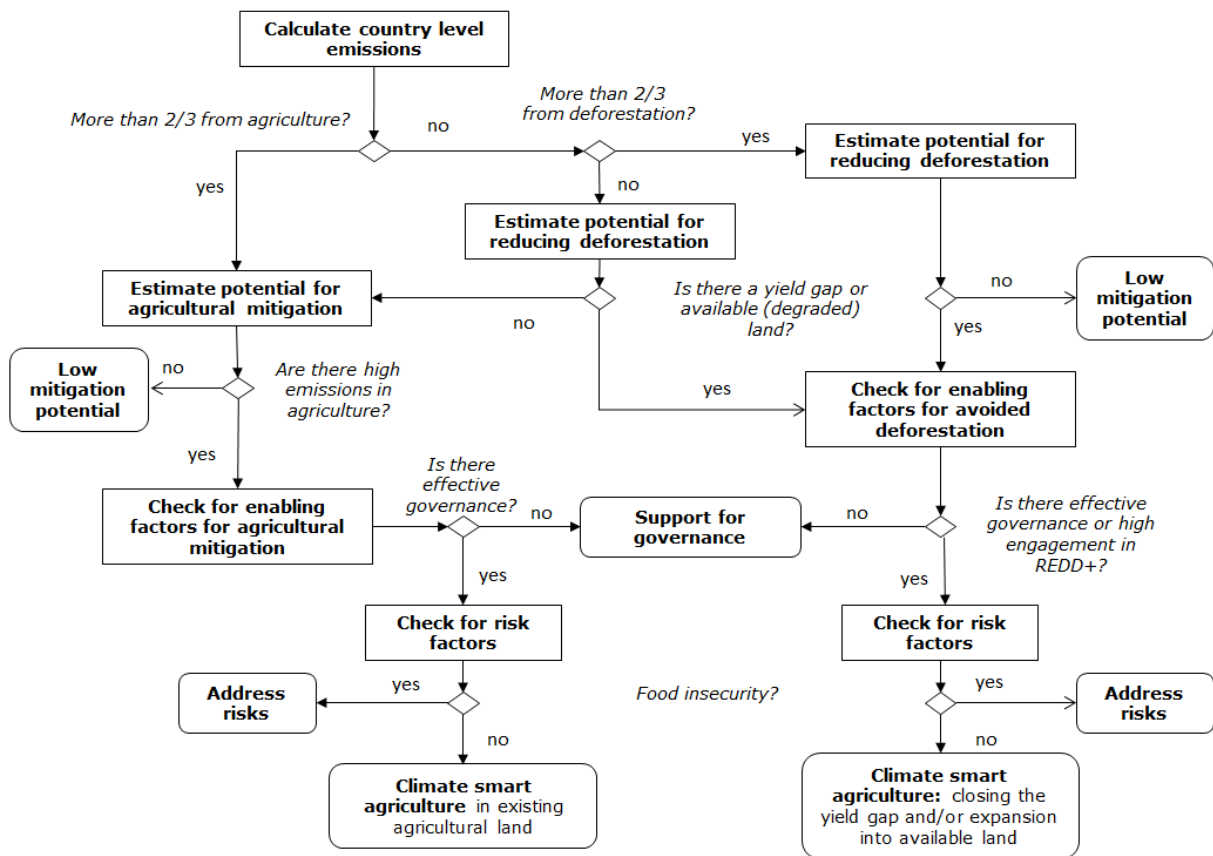
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4

5 Figure 1. National-scale assessment of the need, potential and risk of implementing

6 interventions to reduce emissions from agriculture and agricultural driven deforestation.

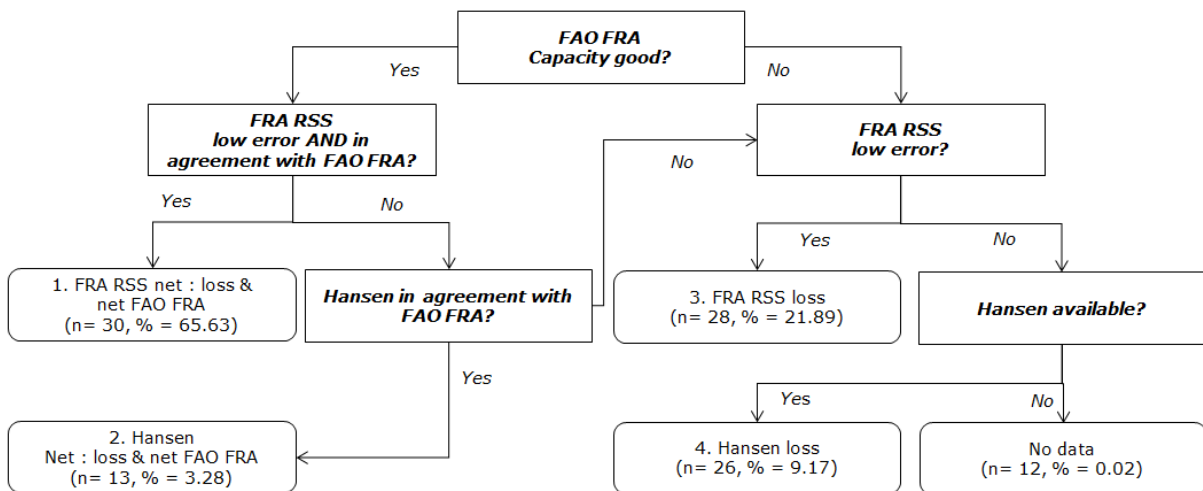
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2

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

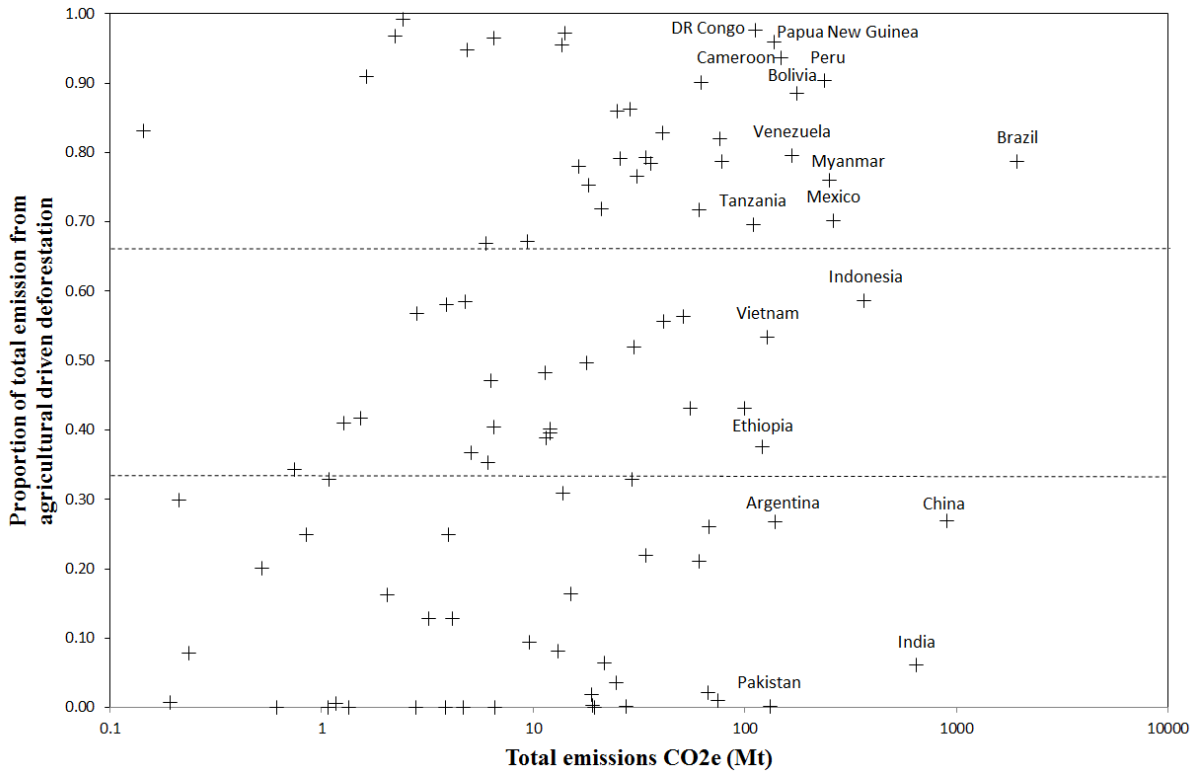


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6

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

4

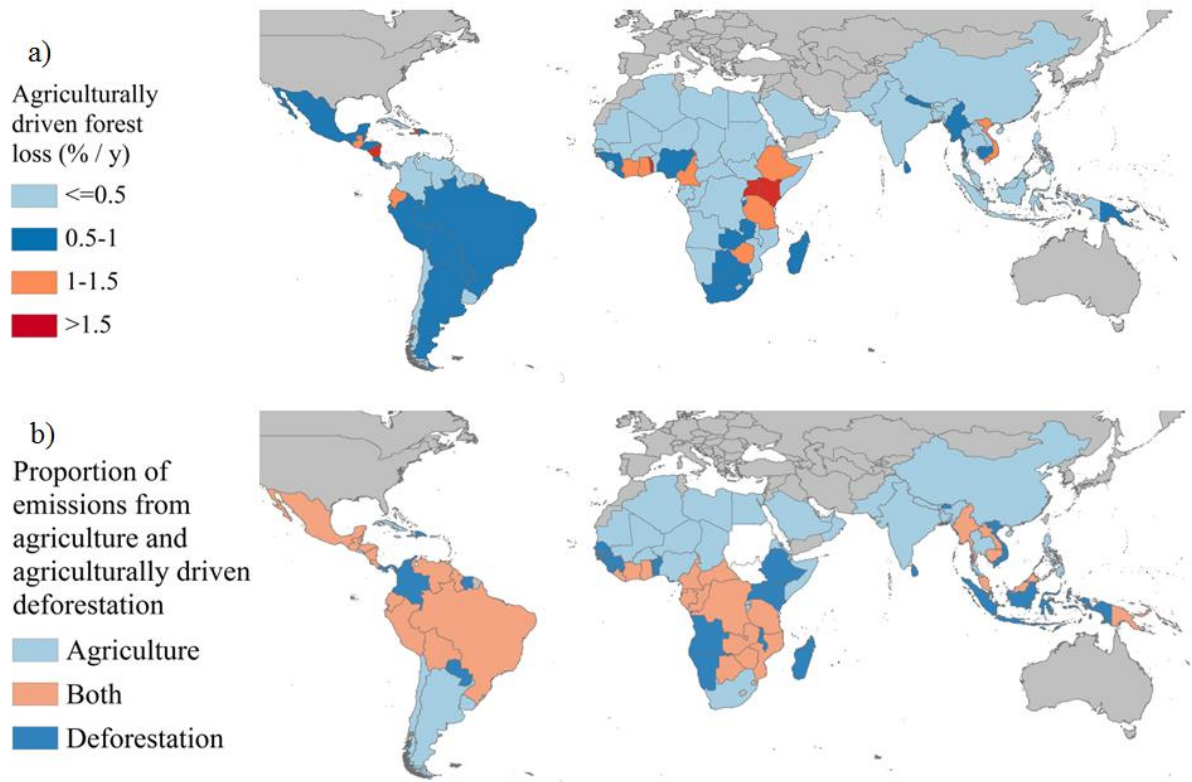


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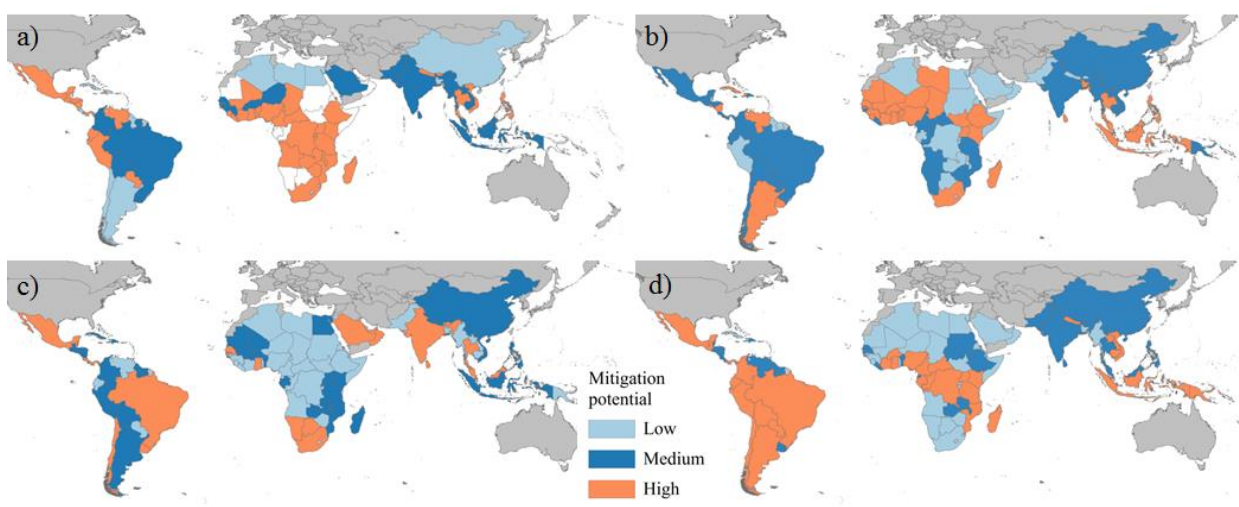
7 Figure 4. Total CO₂e emissions (annual AGB and BGB removals on forest land converted to
 8 agriculture (2000-2010/12) plus annual agricultural emissions (2010)), and the proportion of
 9 the total emissions from agricultural driven deforestation (1 = 100% emissions from
 10 agricultural driven deforestation, 0 = 100% emissions from agriculture). The 17 countries
 11 with emissions >100 Mt are labelled (n=95). The horizontal lines distinguish the groups
 12 where total emissions are: >66% from agriculture (lower third), 33-66% from agriculture-
 13 driven deforestation and agriculture (middle third) and >66% (middle third) from agriculture-
 14 driven deforestation.

15



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



9

1

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