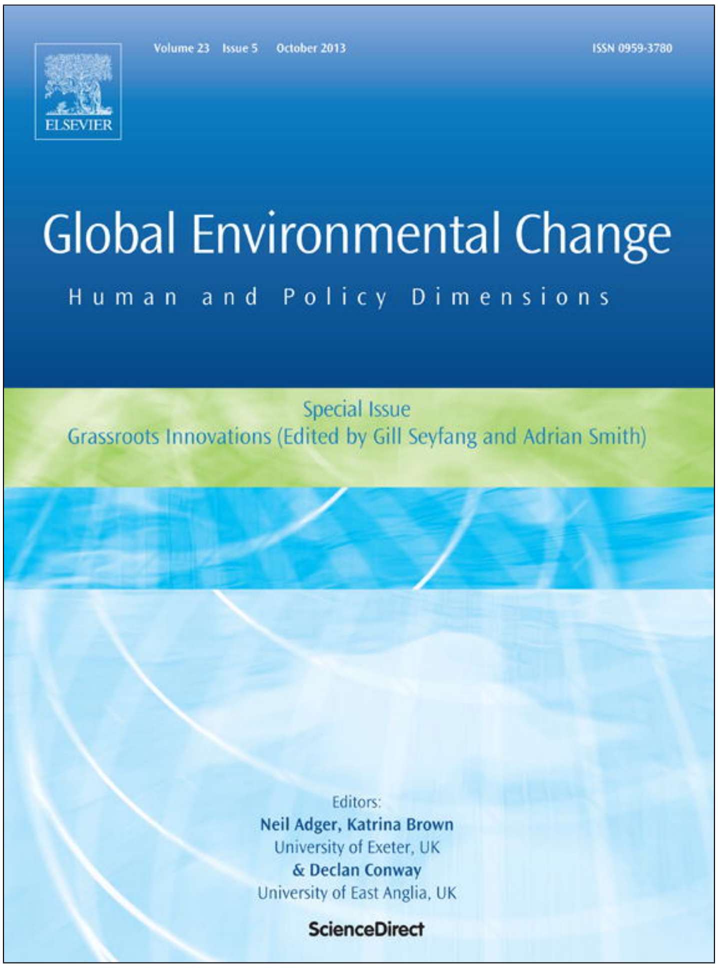
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Estimating the world's potentially available cropland using a bottom-up approach

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ABSTRACT

Previous estimates of the land area available for future cropland expansion relied on global-scale climate, soil and terrain data. They did not include a range of constraints and tradeoffs associated with land conversion. As a result, estimates of the global land reserve have been high. Here we adjust these estimates for the aforementioned constraints and tradeoffs. We define potentially available cropland as the moderately to highly productive land that could be used in the coming years for rainfed farming, with low to moderate capital investments, and that is not under intact mature forests, legally protected, or already intensively managed. This productive land is underutilized rather than unused as it has ecological or social functions. We also define potentially available cropland that accounts for trade-offs between gains in agricultural production and losses in ecosystem and social services from intensified agriculture, to include only the potentially available cropland that would entail low ecological and social costs with conversion to cropland. In contrast to previous studies, we adopt a "bottom-up" approach by analyzing detailed, fine scale observations with expert knowledge for six countries or regions that are often assumed to include most of potentially available cropland. We conclude first that there is substantially less potential additional cropland than is generally assumed once constraints and trade offs are taken into account, and secondly that converting land is always associated with significant social and ecological costs. Future expansion of agricultural production will encounter a complex landscape of competing demands and tradeoffs.

1. Introduction

Land is a scarce resource at a global scale. Increases in both human population and per capita consumption of material goods have increased demand for commodities produced from the land (Lambin and Meyfroidt, 2011). Meanwhile, land degradation and climatic change threaten the current base of productive land. Intensification of land use has the potential to satisfy the bulk of future increases in demand (Godfray et al., 2010). However, additional conversion to croplands will be unavoidable. By 2030, an additional 81 to 147 million hectares (Mha) of cropland will be needed compared to the 2000 baseline. Rapid urbanization, bioenergy policy mandates, forest plantations, and new protected areas are also competing for land access (Meyfroidt and Lambin, 2011). Total additional land demand is likely to range from 285 to 792 Mha between 2000 and 2030 (Lambin and Meyfroidt, 2011). The perception that we are approaching a limit in available productive land is growing, highlighting the need for improved information on land availability.

We define *potentially available cropland* (PAC) (sometimes referred to as land reserve, underutilized, or spare land) as the

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moderately to highly productive land that could be used in the coming years for rainfed farming, with low to moderate capital investments, and that is neither under intensive use, legally protected, nor under intact mature forest cover. Our definition excludes areas that could only be put into cultivation with major investments – e.g., irrigation or costly soil reclamation – and for which the ecological cost of conversion in terms of biodiversity and carbon storage is known to be very high – *i.e.*, protected areas and intact or little disturbed forests (Gibson et al., 2011).

PAC, while underutilized in terms of agricultural production, is used for a variety of purposes, often as extensive grazing lands or long-term fallows. PAC may also have ecological or social functions such as ecological corridors, hunting-and-gathering grounds, recreation areas, sacred land, or protection against landslides. Decision-makers must consider the tradeoffs between the gains in agricultural production from expanding croplands and the associated losses of ecosystem and social services (DeFries et al., 2004). We therefore also define *potentially available cropland that accounts for trade-offs* (PACt), as the subset of PAC that could be converted at relatively low ecological and social costs – recognizing that this cost is never nil and will vary with differing perspectives and priorities (Fig. 1). Our reconceptualization of PAC therefore shifts away from a "finite stock" view to a "gradient" or "continuum" view – i.e., how social and ecological costs of land conversion increase with land use expansion.

Past estimates of PAC have adopted either a "residual approach" – i.e., estimating the total area that is agro-ecologically suitable and then excluding cultivated areas and, in some cases, intact forests, protected areas and densely populated areas (Ramankutty et al., 2002; IIASA/FAO, 2012) – or a "categorical approach" – i.e., identifying specific categories of land use/cover that could be converted to croplands (Campbell et al., 2008; Cai et al., 2011). Historically, vast amounts of forests and other lands fulfilling valuable social or ecological functions have been converted for agriculture, and still are in some parts of the world. Assuming that this trend will continue led to estimates of PAC ranging from 1600 to 1900 Mha, an area that is larger than the 1500 Mha of land already devoted to crops. Young (1998, 1999, 2000) criticized these estimates, suggesting that cultivable land was overestimated; land already cultivated was underestimated; and the needs for land for alternative uses were insufficiently taken into account. A recent FAO report (Alexandratos and Bruinsma, 2012) still identifies a generous 1400 Mha of prime and good land that could be brought into cultivation if needed. Our more conservative approach integrates more comprehensive social and environmental constraints, in a

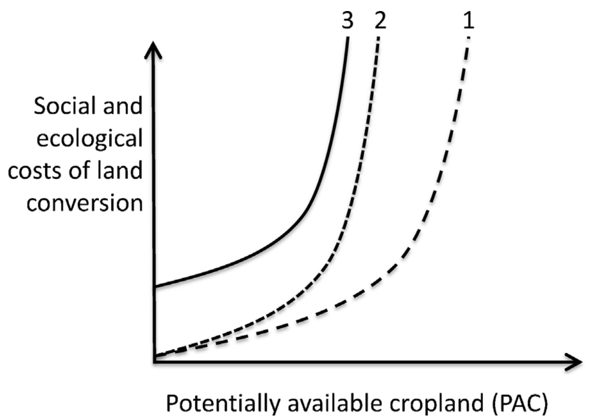

Fig. 1. Potentially available cropland (PAC) as a function of the ecological and social costs of land conversion: (1) top down estimate of PAC; (2) bottom up estimate of PAC based on various constraints; (3) potentially available cropland that accounts for social and ecological trade-offs (PACt). Consideration of constraints and trade offs reduces PAC and increases the cost to access PAC.

context where indigenous rights and the value of ecosystem services are better acknowledged.

IIASA/FAO (2012) has produced a global database of agro-ecological zones that is widely used to identify land suitable for different cropping systems. IIASA/FAO (2012) identified 3100 Mha as good to very suitable for production of five key crops with mixed input levels, accounting for terrain, soils, temperature, and water availability. Of these lands, 1000 Mha are already cultivated. [Of the 1510 Mha under cultivation worldwide, 510 Mha are on land with moderate or lower suitability according to IIASA/FAO (2012).] This leaves 2100 Mha of land suitable for agricultural expansion including forests and protected areas. A recent World Bank report (2010) estimated that the non-cultivated area that is suitable for cropping, while being non-forested, non-protected, and populated with less than 25 persons/km^2, amounts to 445 Mha globally. Using the most recent release of the Global Agro-ecological Zones database (GAEZ version 3.0, IIASA/FAO, 2012), we estimated 598 Mha, considering the same constraints. A large fraction of this area is concentrated in a few countries – e.g., Brazil, Argentina, Democratic Republic of Congo, Mozambique, and Russia.

PAC estimates have great policy significance – e.g., for bioenergy policies, standards of sustainable agricultural production, or regulations on large-scale land acquisitions by foreign actors (The World Bank, 2010; Nalepa and Bauer, 2012). The objective of this study is to evaluate the current size and geographic distribution of PAC and PACt accounting for the constraints and tradeoffs associated with their conversion. In contrast to previous exercises, we adopt a "bottom-up" approach by looking for PAC based on detailed, fine scale observations and expert knowledge for regions where previous analyses have identified large PAC reserves. Our time horizon focuses on the next five to ten years, thus allowing us to ignore potential future changes in demand, technology, infrastructure, labour force distribution, and climate.

2. Social and physical constraints to land conversion

There are several physical and social challenges to land conversion for agriculture within a short time horizon (Table 1). Ignoring these constraints leads to an overestimation of PAC. Even where broad-scale assessments would consider agro-ecological conditions to be suitable for agriculture, other biophysical factors may limit the potential to expand croplands. Climate variability affects crop production in drylands and susceptibility to soil erosion or salinization render some lands marginal for crop production. Landscape fragmentation, due to the spatial heterogeneity in biophysical conditions and history of land occupation, also influences the accessibility of underutilized lands. In densely populated, long cultivated regions in East Asia, for example, one finds shards of underutilized lands next to slivers of productive land. In remote places, underutilized lands occur in larger fragments.

Economic constraints create disincentives for converting or intensifying potential cropland. Lack of transportation infrastructure limits access to local and international markets (Soares-Filho et al., 2006). Areas with only extensive cropland will also require coordinated investments to develop the supply chains associated with mechanized production and input use. High costs are involved in the cultivation of areas with degraded soils or with invasive species that outcompete crops.

Labour availability, qualifications, and cost can constrain agriculture in areas with significant supplies of PAC. Labour can be scarce due to rural-to-urban migration or along a sparsely populated frontier. For example, ageing farmers and a lack of entrepreneurial spirit in regions of the former Soviet Union after decades of collectivized farming have contributed to the under-utilization of croplands (Ioffe et al., 2004).

Table 1
Main constraints to the conversion of potential croplands.

Social	Administrative, political	Economic	Physical
-Labour quantity and qualifications	-Land access	-Lack of capital for conversion and investment	-Climate variability
-Cultural attitudes	-Security of land tenure	- Domestic and international market access	-Soil susceptibility to erosion
-Indigenous reserves	-Conflicts and political instability	- Transportation infrastructure	-Landscape fragmentation
- Relied on for sustenance by local communities	-Weak institutions and corruption	- Industry supply chain	-Presence of mineral deposits, mining concessions
- Small, fragmented land holdings	-Land zoning	-Narrow local markets	-Topography
	- Nationalistic policies restricting access to foreign capital or owners	-Access to credit	-Wetlands
		-Transaction costs for land titling	

Insecure land tenure may constrain both agricultural expansion into underutilized lands, and intensification by local communities. Where farmers have to pay the cost of titling their lands, only those holding valuable parcels of land near cities will find it economically worthwhile to formalize land ownership and intensify production. Agribusinesses may also shy away from cultivating PAC with undefined or fragmented ownership because of the transaction costs and risks involved in obtaining consent from local communities. Alternatively, weak governance or autocratic and corrupted regimes could increase land access by highly-capitalized investors willing to pay for it. The political instability and civil wars that have plagued parts of Africa hindered large-scale investment from outsiders and limited the capacity to expand croplands.

Other political factors, including zoning schemes that restrict some forms of agricultural uses, can limit access to underutilized land. For example, a recent Argentinean forest law requests that all provinces define forest types for which agriculture expansion would be restricted. Indonesia's degraded land is often difficult to access due to land zoning that masks degraded and previously cleared land within forest estates that are not zoned for agriculture. Brazil's forest code also limits the total area that can be converted in each property.

Of course, the above constraints are not absolute, but they are relevant for the short-term horizon of this PAC estimate. Over time, with sufficient capital investments, technology, and policy and demographic changes, most constraints can be overcome – and were overcome in the past –, but often at high ecological, economic, and social costs.

3. Environmental tradeoffs of PAC categories

In addition to constraints to land conversion for agriculture, there are social and ecological tradeoffs. Impoverished and food-insecure people often occupy marginal lands, and they could be displaced if large-scale agribusiness moves in. Beyond protected areas' contribution to biodiversity protection, other habitats still have value as buffer zones and ecological corridors. Many land cover types contribute to terrestrial stocks and sinks of carbon. PAC falls under various categories of land use or cover, each with their specific tradeoffs.

Degraded or marginal lands: Discussions of potential new crop, bioenergy, or timber plantations often target degraded or marginal lands. However, regional and global estimates of degraded land are generally unreliable. The investments required to restore these lands for crop production are difficult to evaluate. In Brazil, so-called "degraded pastures", having lost part of their soil fertility after years of grazing, still have higher stocking rates than many rangelands in drylands. Other degraded lands can be more expensive to rehabilitate, such as soils affected by salinization or chemical contamination, or lands whose use is impeded by invasive species.

Abandoned agricultural lands: Previously cultivated lands are often assumed to be eligible for re-cropping or bioenergy at a low environmental cost (Campbell et al., 2008; Cai et al., 2011). Land abandonment often follows rural to urban migration and economic changes, but croplands are also abandoned because they were marginally productive. The reestablishment of vegetation following abandonment sequesters carbon, and conserves soils and water resources. Agricultural abandonment may restore habitat for wildlife but also decreases habitat for species adapted to farmland. The cause and time since abandonment influence the barriers to re-establishing production on these lands.

Idle croplands and fallow lands: Every year, large cultivated areas are either not planted or harvested due to efforts to restore soil fertility, poor climatic conditions, crop failures, or changing financial incentives. The extent of idle croplands is large, as 10–20% of croplands in the U.S. are not harvested each year (including land in the Conservation Reserve Programme) (Nickerson et al., 2011). These lands are one of the most accessible categories of PAC and yet they contribute to biodiversity and soil conservation. Fallow lands also exist across the tropics, particularly in Africa and Southeast Asia, as part of shifting cultivation, and contribute to restoring soil fertility. Some estimate that there are over 200 Mha of fallow lands from shifting cultivation in forests and savannas (Frolking et al., 2009), but they are progressively being replaced by large-scale intensive permanent agriculture in some regions.

Disturbed and secondary forests: Disturbed and regrowing forests are found throughout the world, but particularly along agricultural frontiers and where logging and fuelwood collection activities are widespread. In Latin America during 2001–2010, woody vegetation expanded over 36 Mha (Aide et al., 2013). The regrowth of these forests may account for a large fraction of the land carbon sink (Pan et al., 2011). The biodiversity values of secondary forests can also be significant (Bowen, 2007). Other ecosystem services provided by secondary forests such as regulating the water cycle are generally important but highly variable (Chazdon, 2008). Because secondary forests are often easier to clear than old growth forests, in terms of labour, access, and legal restrictions, they frequently become the target for agricultural expansion.

Low-intensity grazing land, natural grasslands and savannas: Naturally non-forested lands are also considered as sources of PAC. Extensive grazing lands are found in Eastern, Southern and Sahelian Africa, Central Asia, and subtropical and temperate South America. While these ecosystems store less carbon than forests, they can contain sizeable carbon stocks and notable biodiversity. Tropical savannahs are also hotspots of vertebrate biodiversity (Grenyer et al., 2006) and are used extensively by smallholders and pastoralists.

4. Case studies

The constraints and tradeoffs associated with cropland expansion play out differently in each region. We evaluated the availability, constraints, and tradeoffs entailed in cropland expansion for several case study regions that are often assumed to hold substantial PAC: the Chaco region, the Brazilian Cerrado, the Brazilian and Bolivian Amazon, the Congo basin, Indonesia, and Russia (Fig. 1). PAC was estimated in each of these regions based on the best available and most recent spatial data, and expert judgement for that region (details in on-line Supplementary Material, including a detailed breakdown of PAC estimates for each region in Table S1).

4.1. The Gran Chaco region of South America

Subtropical and temperate dry forests and savannas of Argentina, Bolivia and Paraguay, called the Gran Chaco, represent a large continuous woody ecosystem where soybean and planted pastures are expanding rapidly (Grau et al., 2005; Aide et al., 2013). The Gran Chaco covers about 139 Mha, of which 89 Mha are still covered by woodlands (forests and shrublands) and 29 Mha by grasslands (Clark et al., 2010). Most of this area is used for timber, firewood and charcoal extraction, and extensive grazing (Grau et al., 2008).

4.1.1. Availability

Climate and soils limit crop production on much of the remaining uncultivated land. Excluding areas with soil restrictions (salinity, water table) and rainfall below 700 mm per year (considered the minimum for reliable rainfed agriculture), we identified circa 44 Mha for PAC, with about 7 Mha being located in protected areas. This leaves 37 Mha of legally available PAC: 23 Mha in woodlands and 14 Mha in grasslands (both natural and planted grass-dominated vegetation). Of this, 9 Mha are located in Paraguay, 15 Mha in Bolivia, and 13 Mha in Argentina. Note that some areas of current croplands fall within unfavourable soil and climate conditions.

4.1.2. Constraints

Argentina has recently approved a forest law requiring each province to define areas that can and cannot be converted to agriculture, based on varying criteria. Current restrictions – expected to be revised every five years – cover almost 9 Mha, leaving approximately 4 Mha of PAC in Argentina's Chaco. In addition, Argentina and Brazil have adopted new laws to limit land tenure by foreigners, and Bolivia and Paraguay could follow, thus reducing the capacity to access PAC.

Conflicts between expanding agribusinesses and local populations, both creole and indigenous, have increased in recent years and may influence future access to PAC. The political influence of local and indigenous people varies markedly among and within countries. Most indigenous land claims refer to both real estate and resource accessibility, even where land legally belongs to the state or private owners. The precise area with disputed tenure related to indigenous rights claims is difficult to determine but it certainly reduces the PAC accessible for conversion by non-indigenous actors.

PAC are vulnerable to rainfall fluctuations and soil degradation, in particular due to changes in the water table resulting in soil salinization (Jobbágy et al., 2008). New drought-resistant cultivars could open new PAC beyond current biophysical constraints. In remote areas, representing about 50% of the total land area, road access to ports is a major economic constraint.

4.1.3. Trade offs

The Chaco forests represent a major carbon reservoir, storing 6.8 Gt of biomass carbon (Gasparri et al., 2008). We computed PACt under three scenarios, that would be associated with a conservation of 50%, 75% and 100% of the above-ground carbon stocks of the biome. This led to the further exclusion of, respectively, 8, 14 and 20 Mha thus leaving 20, 14 and 8 Mha of PACt.

The Chaco harbours significant biodiversity, including the southernmost distribution of large iconic species (anteaters, jaguars, peccaries). Many areas with high species richness are included in protected areas or other designated areas with limitations for agricultural expansion. However, species distributions in PAC are poorly understood, and fragmented forests retain habitat value as corridors or source regions for mobile populations. Finally, rural communities and indigenous populations, in particular, are often highly marginalized and rely on forest resources for their sustenance. The potentially affected population includes tens of thousands of people. They could be adversely affected both economically and culturally by conversion of their lands to large-scale agriculture, unless they would engage in intensive agriculture themselves. Indigenous communities are recently shifting from hunting and gathering to cattle ranching and cultivation.

4.1.4. Conclusion

The Gran Chaco includes large areas of "degraded" natural ecosystems with low population density, but ecological value and land claims by indigenous communities. The Chaco ecosystem has been converted rapidly in recent years, leading to conflicts over biodiversity conservation, carbon storage and the rights of local populations. Current legal and environmental constraints do provide some safeguards against encroachment into sensitive areas in the short-term, at least in Argentina.

4.2. The Brazilian Central Savanna Biome (Cerrado)

The Cerrado biome is a rich and large neotropical savanna ecosystem encompassing a mosaic of grassland, shrubland, and woodland landscapes over 208 Mha (26% of Brazil). Largely unaltered prior to 1970, the Cerrado has recently been subject to rapid agricultural expansion (Bustamante and Ferreira, 2010), at a rate much higher than in the Amazon (14,179 km^2 vs. 6451 km^2 of deforestation in the Amazon in 2010). The Cerrado has become the country's most important agricultural frontier, with large-scale production of soybeans and beef for export (Jepson et al., 2010).

4.2.1. Availability

In 2002, 60.5% of the Cerrado region was still covered with natural vegetation (mainly shrublands), including 7 Mha of secondary forests and 23 Mha of natural grasslands used for cattle ranching (Sano et al., 2001, 2010). An additional 7.5% of remaining Cerrado vegetation was cleared between 2002 and 2011 (MMA, 2011). Cultivated pastures occupy more than 25% of the biome (Sano et al., 2010). Based on soil properties, topography, and current environmental legislation, 30 Mha of these pastures are suitable for intensive agriculture (Goedert, 1988) and up to 60 Mha of remnant vegetation could be converted in compliance with the current and proposed regulations of the Brazilian Forest Code (Sparovek et al., 2010). Based on the 2012 legislation, an increase in deforested areas of 13.5% of the remaining Cerrado formations could occur by 2050 (Ferreira et al., 2012).

4.2.2. Constraints

Rainfed agriculture in the north and northeast of the Cerrado, towards the semi-arid Caatinga biome, would require technical investments to circumvent water limitations, in addition to acidic soils with high aluminium and low nutrient contents (Motta et al., 2002). At least 50% of the Cerrado's cultivated pastures are severely degraded (Oliveira et al., 2004) and dominated by invasive species. Crop expansion over pastures and consequent livestock reallocation would require substantial capital investments, government subsidies, and technical assistance. The rapid expansion of the ethanol industry in the Cerrado also intensifies competition for land that is suitable for sugarcane production.

The remaining non-agricultural areas in the unprotected Cerrado are mostly located in its northern region. They have a low accessibility and are likely to be preferentially considered for future carbon credit markets, as conserving the Cerrado is drawing domestic and foreign attention. The Federal government of Brazil committed to reduce the Cerrado deforestation rate by 40% by 2020 relative to 1999–2008. Remnant vegetation areas in the Cerrado have also become a primary target for extra-property legal reserves for farms without sufficient natural vegetation to comply with environmental legislation.

Most PAC areas are privately owned, in a well-defined land tenure system. The Brazilian government restricts foreign land ownership. Finally, the lack of a qualified labour force may limit mechanized agriculture in the short-term, particularly in the Cerrado-Caatinga transition area.

4.2.3. Trade-Offs

Cropland expansion in the Cerrado, whether in pastures or natural vegetation areas, will have negative social and environmental impacts. The removal of remnant vegetation may permanently compromise ecosystem services, including the above and below-ground carbon stocks of 33.6–45.4 MgC/ha (Potter et al., 2009; Miranda et al., in press). The Cerrado is a biodiversity hotspot. The conversion of pastures and forest fragments could induce further biodiversity losses. Cultivated areas would require high inputs of fertilizers and cultivation on fragile (sandy) soils, as in the upper Araguaia-Tocantins basin, with likely hydrological impacts (Costa and Pires, 2010). The expansion of large agribusiness companies, especially near the Caatinga biome, could trigger further migration of poor smallholders to urban areas.

4.2.4. Conclusion

Gentle topography, high rainfall, low land prices, large public investments in infrastructure, and new crop varieties turned the Cerrado into a major agricultural frontier. Its north-eastern region (across the Maranhão, Piauí, Tocantins and Bahia States) is currently the most active land conversion area in Brazil. The Cerrado and its pasturelands are still attractive for further expansion of both cattle ranching and mechanized, rainfed grain production. Expanding cropland by converting pastures while intensifying cattle ranching could free up 10 Mha of PACt in the Cerrado.

4.3. Brazilian and Bolivian Amazon

The Amazon arc of deforestation accounted for more than 50% of all tropical forest losses worldwide in 2000–2005 (Hansen et al., 2008). More than four decades of agricultural expansion, driven by boom and bust cycles of timber, rubber, beef, and soybean production, have left a patchwork of agriculture and forest, including degraded forests from logging or fire, and secondary forests from agricultural abandonment. In 2008, nearly 85% of deforested areas in the Brazilian Amazon (45 Mha) were used for cattle ranching (EMBRAPA and INPE, 2011). Improving management for community development and sustainable production on existing cleared areas is becoming a priority in the region.

4.3.1. Availability

Using satellite data, we identified 32.5 Mha of pasture on deforested lands along the arc of deforestation in Brazil and Bolivia – excluding deforested areas under intensive management for grain or timber production during 2001–2010 (1.6 Mha). Most of this deforested area was cleared prior to 2000. Deforestation during 2000–2010 accounted for only 11% (4.2 Mha) of the area in pasture in 2010.

Degraded and secondary forests constitute an additional reserve of PAC and have been targeted for agricultural expansion based on lower carbon stocks and proximity to agricultural activities. Understory fires damaged nearly 6 Mha of forest in the Brazilian and Bolivian Amazon during 1999–2010 (Morton et al., 2013). Agricultural lands that were abandoned between 2002 and 2006 and remained forested in 2010 totalled <0.2 Mha. Previous studies, which estimated that 20–36% of deforested lands in the Brazilian Amazon were in some stage of secondary forest (Lucas et al., 2000; EMBRAPA and INPE, 2011), examined a single point in time rather than following the dynamics of abandonment and re-clearing over time.

4.3.2. Constraints

The greatest constraint on cropland expansion in Amazonia is competition from existing land uses. Most deforested lands are currently managed for low intensity cattle or agricultural production (84%). Converting pastures to cropland, with a simultaneous intensification of pastures, requires substantial capital for farm machinery, seeds, fertilizers, and land preparation (Vera-Diaz et al., 2008). Access to capital is currently restricted in approximately 50 municipalities in the Brazilian Amazon as part of anti-deforestation measures (MMA, 2011). Ranching and farming operations differ significantly. Developing the necessary expertise to operate and market agricultural products could be a barrier to cropland expansion, and would require cultural changes.

In some regions, the size of rural population may limit crop expansion. Extensive ranching operations occupy large areas but employ few workers – e.g., 1 person per 400 ha of pasture (Butler, 2011). Many cropping systems require more manual labour for year-round or seasonal harvesting – e.g., oil palm production can be 40 times more labour intensive than cattle ranching. Given the low population density in many frontier areas, a labour force would have to be brought in to support large-scale oil palm production slated to replace extensive pasture systems.

PAC in Amazonia is highly fragmented. Small parcels (5–10 ha) of pasture and secondary forest are widely distributed along the frontier (totalling 0.1 Mha), presenting a challenge for coordinated programmes to expand crop production on abandoned lands. Access to large areas of burned forests may be restricted under Brazil's Forest Code if these areas are part of the legal forest reserve.

Slope is a more important constraint on crop expansion in Amazonia than transportation infrastructure for market access (Jasinski et al., 2005). Although areas with 16% slopes are used for crop production in many regions (IIASA/FAO, 2012), current cropland in Amazonia predominantly occupies flat areas. More than 80% of current croplands along the arc of deforestation occupy areas with 0–2% slopes. In contrast, <50% of pasture and degraded forests in Amazonia had slopes <2%. We considered areas with slopes >16% as very marginal for crop production (1.3 Mha), while PAC with slopes between 2 and 16% was considered marginally suitable (12.8 Mha) on a 5–10 year horizon.

Excluding the portion of the PAC reserve with limited labour (<1 person per km^2, 8.9 Mha), within existing protected areas or indigenous lands (1.2 Mha), or likely degradation from previous land use (1.8 Mha), we estimated a total of 12.4 Mha of PAC in burned forests, secondary forests, and pasture along the Amazon arc of deforestation.

4.3.3. Tradeoffs

The estimate of PACt for the Brazilian and Bolivian Amazon excluded PAC with high biodiversity, high carbon stocks, or pastures from recent deforestation. Areas with biodiversity tradeoffs (1.9 Mha) were identified using a 10 km buffer zone around existing protected areas and indigenous reserves. Burned and secondary forests were also excluded from PACt because they typically retain large carbon stocks (Cochrane and Schulze, 1999). Areas of recent deforestation were excluded because, in Brazil, government and industry-led policies restrict crop production on recently cleared lands (Macedo et al., 2012). Our estimate of total deforestation in 2001–2010 was 5.7 Mha, of which 4.2 Mha overlaps with pasture areas. Most of the pasture expansion from recent deforestation was already accounted for in the other constraints. Thus, only another 1.5 Mha of recent deforestation was subtracted in our PACt estimate.

4.3.4. Conclusion

As in the Cerrado, extensive pasture areas offer the potential to increase rainfed crop production in the Amazon without additional deforestation, provided it is accompanied by a simultaneous livestock intensification (Macedo et al., 2012; Bustamante et al., 2012). However, not all pastures are suitable for crop production and the suitably of sloped pastures may have been overestimated in previous studies. In 2010, only 45% of existing pastures outside of protected areas had slopes similar to current croplands. Given the long history of land clearing in Amazonia and high prices for agricultural commodities in recent years (Morton et al., 2006), unfavourable slopes and related environmental constraints (e.g., rooting depth, soil fertility) may partially explain the lack of cropland expansion into pasture in some areas with suitable climate and existing transportation infrastructure (Jasinski et al., 2005). Efforts to convert extensive pasture lands to more intensive production systems will also confront substantial social and economic hurdles, including necessary on-farm capital investments and improvements in transportation infrastructure. PAC reserves in Amazonia are widely distributed across >2000 km.

4.4. Congo (Democratic Republic, DRC)

The DRC, by its large area (235 Mha) and favourable climatic conditions, is a key African country for agricultural expansion. The central part of DRC is covered by 117 Mha of tropical rain forests and swamp forests, while 63 Mha of Miombo woodlands and savannas extend at the northern and southern fringes of the Congo Basin (de Wasseige et al., 2009). Cropland area is only 32 Mha, or 15% of the territory (FAO, 2003), equally distributed in the forest domain and in savannas. The average population density is low (26 hab/km^2), but some areas are densely populated (Southern and Eastern DRC, around Kinshasa) and population is growing fast (2.84%/yr). Seventy percent of the population is rural and depends directly on small-scale agriculture. The demand for agricultural land would more than double in the next 20 years with current technologies (Zhang et al., 2006). Yet, the agricultural sector has drastically declined since 1961. In 2000, agricultural exports represented 15% of their 1973 value. To revitalize the sector, the DRC Parliament ratified in 2011 a new agricultural law to protect smallholder agriculture and promote investments.

4.4.1. Availability

We estimated PAC based on two land-cover maps (Verhegghen et al., 2012). We assumed that humid and dry forests should not be converted. The total PAC was 84.5 Mha, mainly in natural savannas (38.6 Mha), degraded forests (5 Mha), natural grasslands (10.5 Mha), and low-intensity agricultural mosaic landscapes (30.4 Mha).

4.4.2. Constraints

Rainfall is not a limiting factor to agriculture in the Congo. Soil fertility is low only in the large area of grasslands on poor sandy soils around Kinshasa. This area is increasingly used for fuelwood and forest plantations for carbon offsets. The presence of mineral deposits precludes further agricultural encroachment in large parts of Southern DRC (Katanga, Kasaï).

Existing, smallholder agriculture provides food to a large rural and urban population. The labour force is largely unqualified. Road transport of inputs and products is extremely expensive due to the low density and poor condition of the network. River navigability recently became seasonally difficult due to lack of maintenance. A major constraint on agricultural expansion is the fragility of the State. Weak control of the territory, numerous territorial authorities, and irregular payment of salaries to civil servants cause corruption and discouragement of local producers. Since the two Congo wars (1996–2003), insecurity is still a major obstacle to agricultural investments, especially in Eastern DRC.

The land tenure system is a compromise between national land ownership and customary rights. Local communities can exploit the land individually or collectively, in accordance with local customs and usages, while industrial investors (by law, only Congolese citizens or companies) receive from provincial authorities a concession to exploit land during a fixed time, according to terms of reference. However, local rights are sometimes uncertain and depend on multiple levels of authority and economic interests (Karsenty and Ongolo, 2011). Conflicts also result from the overlap between forests and mining concessions, especially in areas with abundant mineral deposits.

4.4.3. Tradeoffs

The DRC rainforests contain a large fraction of the African biomass carbon stock and the DRC government is actively engaged in carbon credit markets through forestry. The REDD + national registry includes about 6 Mha of projects in PAC. Any agricultural expansion at the expense of forests – e.g., for oil palm plantations – will cost the DRC future carbon credits. Per the recommendations of the Convention on Biological Diversity, DRC increased the land area under protection status from 10% to 17% to preserve its high biodiversity. This represents an area of 16 Mha, more or less equally distributed across all biomes, with 4 Mha in PAC.

4.4.4. Conclusion

The PAC in DRC is overestimated in global assessments due to the inaccuracy of global land-cover maps on current cropland extent (often in landscape mosaics) and constraints that have been overlooked. Many challenges remain, as demonstrated by the low level of implementation of large-scale investment projects in soybeans, sugarcane, oil palm and maize that were publicly announced. Given a very rapid population increase, smallholder agriculture will be the major focus of agricultural expansion. Lack of credit, insufficient and poor conditions of infrastructure, rudimentary technologies, and political instability all limit the short-term potential for significant large-scale agricultural expansion.

4.5. Indonesia

Indonesia has dramatically increased oil palm production to become the world's leading producer, with plantation acreage doubling in 2000–2010 alone. Large areas of forests have been cleared for logging and agriculture since the 1960s, with oil palm contributing to deforestation directly and indirectly in response to global demand for cheap vegetable oil. While much of the remaining natural landscape without steep slopes is biophysically suited for agriculture or plantations, there is strong international pressure to protect the remaining forests and peat swamp areas. Degraded and previously cleared lands are the focus of several conservation agreements (Gibbs, 2012). There are few options for sustainable cropland expansion in Indonesia outside of degraded areas, anthropogenic "alang–alang" grasslands (*Imperata cylindrica*), logged-over forests, and agricultural mosaics with small-scale agriculture. Fires increase the prevalence of alang–alang grassland, an invasive, fire-tolerant species that quickly dominates following forest clearing, and suppresses other species once established (Fairhurst and McLaughlin, 2009).

4.5.1. Availability

We estimated PAC from satellite-based land cover maps, focusing on alang–alang grasslands, agricultural mosaics, and disturbed forests. Our analysis reveals 63.8 Mha with a potential for agricultural expansion. Nearly half of the 15 Mha of grasslands are concentrated in Kalimantan, where the largest intact forests remain. Papua is largely forested and has little PAC. The 20 Mha of agricultural mosaics is largely found on Sumatra and Kalimantan, but also in Java and the outer islands. Of the 27.6 Mha of disturbed forests, over 75% is in Sulawesi and Kalimantan where logging concessions and lower population densities prevail.

4.5.2. Constraints

Alang–alang grassland can be converted to oil palm by large producers with intensive management and mechanization (Fairhurst and McLaughlin, 2009). Smallholders do not usually have the necessary capital for this, but do convert grasslands to timber or cacao plantations. Communities use agricultural mosaics, thus expansion of large-scale agriculture in these regions is limited.

Indonesia's land concessions or access rights may be a key limitation to cultivating alang–alang and disturbed forests. Some of the alang–alang exist within forest estates identified by the state as off-limit to agriculture, despite ongoing conversion by smallholders. Permits for oil palm plantations and other agricultural uses are more frequently given for forested areas. Often, lands that were previously cleared or logged are already subject to informal claims by local communities, thus increasing the transaction costs of intensifying cultivation by outsiders. Transportation infrastructure, storage and processing plants can be limiting factors in Papua. In Sumatra and Kalimantan, such constraints are less severe due to the presence of oil palm estates.

Because oil palm plantations have high upfront costs, producers often prefer to plant in forested regions where the logging profits help to finance the oil palm plantation. There are thus financial obstacles to expanding in previously cleared areas. Corruption and lack of enforcement of current laws are also major impediments to investments.

4.5.3. Tradeoffs

Converting logged over and secondary forests to agriculture or plantations has substantial impacts on carbon emissions and biodiversity, particularly in Sumatra and Kalimantan where primary forests are dwindling, leaving few undisturbed habitats for wildlife. Intensification in agricultural mosaics has fewer environmental tradeoffs, but could result in community displacement if large-scale agriculture dominates. Cultivating alang–alang is associated with few environmental and social tradeoffs. This grass yields few benefits to local communities outside of animal fodder, thatched roofs, and erosion control. Displacement is less an issue with alang–alang.

4.5.4. Conclusion

Of the 63.8 Mha of possible PAC, a much smaller fraction of grassland and forest areas (7.5 Mha) presents low constraints for expansion, and only 5 Mha of alang–alang grasslands can be considered as PACt. In addition to high carbon stock areas and valuable biodiversity habitats, 2.2 Mha of disturbed forests were excluded due to protected status, 19.5 Mha were only marginally suitable, and another 3.5 Mha already had land rights given for logging and timber plantations. Roughly, 1.6 Mha of agricultural mosaic lands fell within protected areas, leaving 22.4 Mha that are currently used by local communities. Due to fewer environmental and social tradeoffs, grasslands fared better with 1.7 Mha of protected areas, 6.2 Mha of marginally suitable lands, and 2.7 Mha with timber and logging concessions, leaving 5 Mha as PACt. The 20 Mha of mosaic agriculture were excluded, but do provide PAC for small-scale agriculture by local communities. Expanding cropland in Indonesia without clearing additional forests will require improved governance.

4.6. Russia

Russia is the world's largest country, with abundant land suitable for agriculture, some with very productive soils (chernozems or "black soils"), but also large areas constrained by aridity, temperature, or excessive moisture (Nefedova, 2011). Many regions have low population densities. During the Soviet period, collective agriculture was organized in large farms and programmes of cropland expansion were pursued. With the collapse of the Soviet Union in 1991, large-scale land abandonment occurred because of the removal of subsidies to agricultural cooperatives, inefficient production systems, and increased competition with other regions or countries (Prishchepov et al., 2012).

4.6.1. Availability

Russia is often thought to hold a large fraction of the global PAC, especially for wheat. Combining the 20 Mha of cropland area removed from agricultural statistics with areas still enrolled as cropland but that remain unharvested, the total abandoned cropland in Russia was 39–40 Mha in 2009 (Schierhorn et al., in press). Given that agricultural areas in Russia were already contracting before 1990 due to the abandonment of marginal and degraded lands, these 39–40 Mha represent the upper limit of PAC. We therefore only considered this category of land for Russia. Combining a global cropland map for 1993 (Ramankutty et al., 2008) with abandonment rates between 1990 and 2009 by provinces (Nefedova, 2011) yielded 43.5 Mha of abandoned croplands.

4.6.2. Constraints

Of these 43.5 Mha, 6.6 Mha were classified as "very marginally suitable" and 5.1 Mha as "marginally suitable" in GAEZ (IIASA/FAO, 2012). Agriculture is mainly limited by insufficient moisture in south-eastern European Russia, and by cold temperatures in Siberia and the Far East. An additional 0.9 Mha located in protected areas were excluded. Among the areas at least moderately suitable for agriculture, 3.8 Mha were in Western Siberia and the Far East, which are poorly connected to international and national markets. Large investments in transportation, processing, and storage infrastructure would thus be required to make agriculture profitable. Foreign investors have already embarked on such efforts (Visser and Spoor, 2011). Of the suitable area in European Russia, 6.1 Mha were located in districts ("raions") classified as "black holes" – i.e., areas with ageing and unskilled labour force, low and declining yields, and land abandonment until at least 2000 (Ioffe et al., 2004). Overcoming these social and economic constraints would require a major effort but could also provide social benefits.

The 0.6–2.9 Mha of abandoned cropland in fragmented patches that are isolated from other active agricultural lands would be difficult to reclaim. This leaves 18.1–20.5 Mha of PAC in European Russia, of which about 8.5 Mha are located in productive chernozems. These lands are already being progressively reclaimed in southern European Russia and the Volga region (Visser and Spoor, 2011).

Other significant but unquantified constraints can hinder the development of large agro-holdings with foreign capital – i.e., distrust of foreigners, lack of skilled labour force, and land tenure being shared by farm workers among restructured collective farms (Visser and Spoor, 2011). Insecure land tenure, restrictions

Table 2
Comparison of the area of suitable to very suitable cropland that is not forested nor under protected area from the Global Agro-ecological database (GAEZv3.0, IIASA/FAO, 2012) with our "bottom-up" PAC estimates that integrate constraints and trade-offs in three steps (in million hectares).

Country	IIASA/GAEZ suitable area	PAC ignoring constraints	PAC with low constraints	PAC with trade-offs (PACt)	(PACt/GAEZ) × 100
Chaco	29.9	44	28	8.0–20.0	27–67%
Cerrado	36.8	90	27.4	14.4	39%
Amazon	4.4	38.5	12.4	7.4	168%
Congo	38.3	85.4	24	14	37%
Indonesia	16.0	63.8	7.5	5.0	31%
Russia	60.3	43.5	18.1–20.5	8.7–8.9	15%

imposing a minimum farm size in some regions (Visser and Spoor, 2011), and lack of capital, skills and/or entrepreneurial spirit (Ioffe et al., 2004) can prevent smaller farms from reclaiming or even maintaining activities on cropland.

4.6.3. Tradeoffs

Between 0.5 and 0.6 Mha of the PAC are inside or within 30 km of either an "intact forest landscape" – large contiguous patches of undisturbed forests (Potapov et al., 2008) – or one of the 200 ecoregions with a high conservation value and level of threat (Olson and Dinerstein, 1998). Reclaiming these former agricultural lands might entail biodiversity tradeoffs. As for carbon, the abandoned croplands have stored on average 3.7 MgC per ha over the 1991–2000 period (0.47 MgC ha^{-1} yr^{-1}), mainly in the form of soil carbon (Vuichard et al., 2008). Although this figure is an order of magnitude below the rate of carbon accumulation in regenerating tropical forests, 47% (20.4 Mha) of the abandoned cropland are located in areas potentially suitable for growing boreal forests (or temperate forests for a small fraction), which, over the long-term, represent a carbon stock similar to that of tropical forests (Pan et al., 2011). Only 8.7–8.9 Mha in European Russia remains free from the above tradeoffs.

Conversion of former collective farms to private agro-holdings with foreign or domestic capital could be one way to reestablish agriculture on abandoned land. This is likely to generate significant social costs, however, as former collective farms still maintain multiple social functions: supporting local infrastructures and providing employment and a social security net for vulnerable populations (Davydova and Franks, 2006). Poverty, ageing populations and unemployment in Russia became concentrated in rural areas since 1991 (Visser and Spoor, 2011). Mechanized farming with low labour demands is likely to reinforce this trend as, in Russia, small-scale farms contribute more than agro-holdings to rural employment (Lerman and Schreinemachers, 2005).

4.6.4. Conclusion

Of the 43.5 Mha of abandoned cropland in Russia, at least 11.7 Mha can be considered unsuitable for agriculture, while 11.3–13.2 Mha are affected by strong socio-economic constraints. Only 18.6–20.5 Mha in European Russia are affected by few constraints. Of these, only 8.4–8.7 Mha are not associated with major tradeoffs in terms of carbon or biodiversity, are at least moderately suitable for agriculture, are not in a "social black hole" nor in protected areas, and do not suffer from a high spatial fragmentation, thus constituting PACt. This is less than half of the widely cited figure of 20 Mha of readily available land for agriculture, but it is still a significant source of PAC. Whether it is reclaimed through large agro-holdings or small-scale farming will have very different socio-economic implications.

4.7. Synthesis of case studies

Table 2 compares our estimates of PAC and PACt for our six study regions to the area of suitable to very suitable cropland from the GAEZ database (IIASA/FAO, 2012) that is uncultivated, not forested nor under protected area, for the same regions or countries. These figures were extracted through GIS operations from the on-line GAEZ database. The table compares estimates that were defined based on different criteria. Our PAC estimates without any constraint are significantly higher than the IIASA/FAO GAEZ estimates of suitable land (except for Russia) because the GAEZ method does integrate strict agro-ecological constraints to agricultural production. Our PAC estimates that integrate constraints are significantly lower than, or similar to the IIASA/FAO

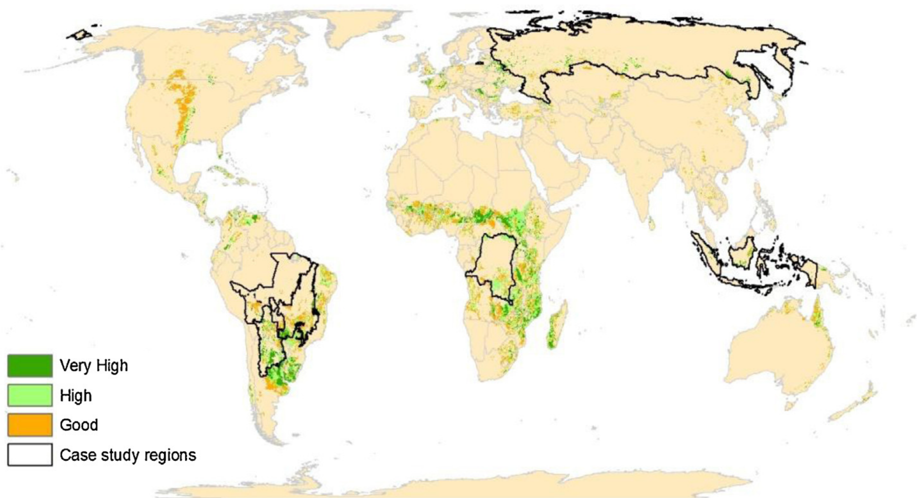

Fig. 2. Location of the six case studies overlaid on the GAEZ v.3.0 map from IIASA/FAO (2012). Only those grid cells with >30% of land with an agro-ecological suitability falling in one of the categories (good, high, very high) are highlighted.

estimates (except for the Amazon) because we did consider both socio-economic and biophysical constraints. These differences also result from different assessments of edaphic constraints, input use, and forest and cropland distributions that are associated with the greater ability of a bottom-up approach to account for fine grained patterns of land use/cover and to integrate more recent data. Including constraints and trade-offs through our bottom-up approach identifies a PACt that is much lower (less than a third on average) than the IIASA/FAO estimates, except for the Amazon. Recent patterns of crop expansion in the Brazilian Amazon did not match the IIASA/FAO spatial patterns of agro-ecological suitability (Fig. 2), possibly due to differences in the level of inputs available for crop production and the inclusion of degraded forests (Morton et al., 2013) as accessible and potentially preferable for clearing compared to intact forests. Rapid expansion of mechanized agriculture in the Brazilian and Bolivian Amazon has shown that moderate to high levels of inputs can turn flat regions into productive croplands.

5. Discussion

Consideration of constraints and trade-offs for a potential expansion of croplands in a bottom-up approach led, in all cases but one, to substantially more conservative estimates of PAC compared to global-scale approaches that only account for agro-ecological suitability. As our estimation of PACt only included carbon and biodiversity trade-offs, our final estimates still include land whose conversion would be associated with other significant social and ecological tradeoffs. We thus provide upper estimates and in no way endorse the conversion of PAC or PACt.

This study provided detailed evidence in support of previous claims by Young (1998, 1999, 2000) that global PAC figures are overestimated. A bottom-up approach is better able to consider more fine-grained, up-to-date, and locally relevant criteria to estimate agro-ecological suitability, current land use/cover, and constraints and tradeoffs associated with land conversion, therefore providing more realistic figures compared to global datasets. The drawback of the bottom-up approach however is a lack of consistency in the criteria used to define PACt: each expert made a judgement based on available data, current land use dynamics, and the social and political context of the region. As a result, costs and benefits of land conversion are not strictly comparable across places.

The level of inclusion of woodlands and disturbed forests in PACt are the most debatable aspect of this assessment. In the Chaco and DRC, most of the PACt was identified in semi-natural disturbed ecosystems, which, although they have been long used for extensive grazing, timber, and fuel extraction, have never been fully converted previously. In the other study regions, the PACt was identified mainly from abandoned cropland and extensive or degraded pastures, where conversion would be associated with lower ecological costs.

This study adopted a time horizon of 5–10 years. The world economy and climate are in constant flux, and land use policies are periodically revised. New technologies may well decrease the cost of investment to bring marginal lands into use. Roads can be built, labour is mobile, and conflicts are not permanent. One should thus replace the binary classification of PAC versus non-PAC by a gradient and dynamic view of costs and benefits associated with land conversion, with more land being converted as prices of land-based commodities increase (Lambin, 2012).

6. Conclusion

The key messages from this study are that: (i) in the near future there is less potential additional cropland than is generally assumed, and (ii) converting land is always associated with social and ecological tradeoffs. Widely-cited sources tend to grossly overestimate potentially available cropland at the global scale, at least on a short-term horizon. There are few remaining places with "free and easy" lands, and multiple land uses – not just cropland expansion – are targeting productive lands. Our results highlight the context-specific constraints and trade off associated with cropland expansion. Overall, key constraints were land occupation by smallholders with little access to capital to intensify, land zoning and concessions, and lack of skilled labour and transportation infrastructures. The tradeoffs were associated with carbon stocks and biodiversity habitats. While most constraints can be overcome on the long run with appropriate policies and investments, tradeoffs will become ever more salient with continuing global environmental change.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.05.005.

References

Aide, T.M., Clark, M., Grau, H.R., Lopez-Carr, D., Levy, M., Redo, D., Bonilla, M., Riner, G., Andrade, M.J., Muniz, M., 2013. The deforestation and reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45, 262–271.

Alexandratos, N., Bruinsma, J., 2012. World agriculture, towards 2030/2050: The 2012 revision. ESA Working Paper No. 12-03, FAO, Rome.

Bowen, M.E., 2007. Regrowth forests on abandoned agricultural land: a review of their habitat values for recovering forest fauna. Biological Conservation 140, 273–296.

Bustamante, M., Ferreira, L.G., 2010. Land use change and the carbon budget in the Brazilian Cerrado. In: Ecosystem Function in Savannas: Measurement Modeling at Landscape to Global Scales. Taylor, Francis, pp. 367–382.

Bustamante, M.M.C., Nobre, C.A., Smeraldi, R., Aguiar, A.P.D., Barioni, L.G., Ferreira, L.G., Longo, K., May, P., Ometto, J.P.H., Pinto, A.S., 2012. Estimating greenhouse gas emissions from cattle raising in Brazil. Climatic Change 115 (3–4) 559–577.

Butler, R., 2011. http://e360.yale.edu/content/feature.msp?id=2415.

Cai, X., Zhang, X., Wang, D., 2011. Land availability for biofuel production. Environmental Science and Technology 45, 334–339.

Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The potential of bioenergy on abandoned agriculture lands. Environmental Science and Technology 42, 5791–5794.

Chazdon, R., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320, 1470–2468.

Clark, M., Aide, T.M., Grau, H.R., Riner, G., 2010. A scalable approach to mapping annual land cover at 250m using MODIS time series data: a case study in the dry Chaco ecoregion of South America. Remote Sensing of Environment 114, 2816–2832.

Cochrane, M.A., Schulze, M.D., 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. Biotropica 31, 2–16.

Costa, M.H., Pires, G.F., 2010. Effects of Amazon and central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. International Journal of Climatology 30, 1970–1979.

Davydova, I., Franks, J.R., 2006. Responses to agrarian reforms in Russia: evidence from Novosibirsk oblast. Journal of Rural Studies 22, 39–54.

DeFries, R.S., Foley, J.A., Asner, G.P., 2004. Land-use choices: balancing human needs and ecosystem function. Frontiers in Ecology and the Environment 2, 249–257.

de Wasseige, C., Devers, D., de Marcken, P., Eba'a Atyi, R., Nasi, R., Mayaux, P., 2009. The Forests of the Congo Basin: State of the Forest 2008. Publications Office of the European Union, Luxembourg, http://dx.doi.org/10.2788/32259.

EMBRAPA & INPE, 2011. TerraClass, available at: http://www.cnptia.embrapa.br/content/terraclass.html.

Fairhurst, T., McLaughlin, D., 2009. Sustainable Oil Palm Development on Degraded land in Kalimantan. World Wildlife Fund, Washington, DC.
FAO, 2003. Multipurpose Landcover Database for DR Congo – AFRICOVER, Available online: In: http://www.africover.org/ (Accessed on 15 Sep 2011).
Ferreira, M.E., Ferreira, L.G., Miziara, F., Soares-Filho, B.S., 2012. Modeling landscape dynamics in the central Brazilian savanna biome: future scenarios and perspectives for conservation. Journal of Land Use Science, http://dx.doi.org/10.1080/1747423X. 2012.675363.
Frolking, S., Palace, M.W., Clark, D.B., Chambers, J.Q., Shugart, H.H., Hurtt, G.C., 2009. Forest disturbance and recovery: a general review in the context of space-borne remote sensing of impacts on aboveground biomass and canopy structure. Journal of Geophysical Research 114, G00E02, http://dx.doi.org/10.1029/2008JG000911.
Gasparri, N.I., Grau, H.R., Manghi, E., 2008. Carbon pools and emissions from deforestation in extra-tropical forests of northern Argentina between 1900 and 2005. Ecosystems 11, 1247–1261.
Gibbs, H.K., 2012. Trading forests for oil yields in the Peruvian Amazon. Environmental Research Letters 7, 011007.
Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.
Goedert, W.J., 1988. A pesquisa agropecuaria no Brasil: o desenvolvimento do potencial agropecuario da regiao dos cerrados. Escola Superior de Guerra, Rio de Janeiro 63p.
Grau, H.R., Gasparri, N.I., Aide, T.M., 2005. Agriculture expansion and deforestation in seasonally dry forests of North-West Argentina. Environmental Conservation 32, 140–148.
Grau, H.R., Gasparri, N.I., Aide, T.M., 2008. Balancing food production and nature conservation in the neotropical dry forests of northern Argentina. Global Change Biology 14, 985–997.
Grenyer, R., Orme, C.D.L., Jackson, S.F., Thomas, G.H., Davies, R.G., Davies, T.J., Jones, K.E., Olson, V.A., Ridgely, R.S., Rasmussen, P.C., Ding, T.-S., Bennett, P.M., Blackburn, T.M., Gaston, K.J., Gittleman, J.L., Owens, I.P.F., 2006. Global distribution and conservation of rare and threatened vertebrates. Nature 444, 93–96.
Hansen, M.C., Stehman, S.V., Potapov, P.V., Loveland, T.R., Townshend, J., DeFries, R.S., Pittman, K.W., Arunarwati, B., Stolle, F., Steininger, M.K., Carroll, M., DiMiceli, C., 2008. Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. Procedings of the National Academy of Sciences of the United States of America 105, 9439–9444.
IIASA/FAO, 2012. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy.
Ioffe, G., Nefedova, T., Zaslavsky, I., 2004. From spatial continuity to fragmentation: the case of Russian farming. Annals of the Association of American Geographers 94, 913–943.
Jasinski, E.W., Morton, D.C., DeFries, R.S., Shimabukuro, Y.E., Anderson, L.O., Hansen, M.C., 2005. Physical landscape correlates of the expansion of mechanized agriculture in Mato Grosso, Brazil. Earth Interactions 9, 18.
Jobbágy, E.G., Nosetto, M.D., Santoni, C.S., Baldi, G., 2008. El desafio ecohidrológico de las transiciones entre sistemas leñosos y herbáceos en la llanura Chaco-Pampeana. Ecología Austral 18, 305–322.
Jepson, W., Brannstrom, C., Filippi, A., 2010. Access regimes and regional land change in the Brazilian Cerrado, 1972–2002. Annals of the Association of American Geographers 100, 87–111.
Karsenty, A., Ongolo, S., 2011. Can "fragile states" decide to reduce their deforestation? The inappropriate use of the theory of incentives with respect to the REDD mechanism. Forest Policy and Economics, http://dx.doi.org/10.1016/j.forpol.2011.05.006.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Procedings of the National Academy of Sciences of the United States of America 108, 3465–3472.
Lambin, E.F., 2012. Global land availability: Malthus *versus* Ricardo. Global Food Security 1, 83–87.
Lerman, Z., Schreinemachers, P., 2005. Individual farming as a labour sink: evidence from Poland and Russia. Comparative Economics Studies 47, 675–695.
Lucas, R.M., Honzak, M., Curran, P.J., Foody, G.M., Milne, R., Brown, T., Amaral, S., 2000. Mapping the regional extent of tropical forest regeneration stages in the Brazilian Legal Amazon using NOAA AVHRR data. International Journal of Remote Sensing 21, 2855–2881.
Macedo, M., DeFries, R., Morton, D., Stickler, C., Galford, G., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Procedings of the National Academy of Sciences of the United States of America 109, 1341–1346.
Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: prospects for an end to deforestation. Annual Review of Environmental Research 36, 343–371.
Ministerio do Meio Ambiente (MMA), 2011. Portaria de N(175, de 24 de Maio de 2011.
Miranda, S.C., Bustamante, M., Palace, M., Hagen, S., Keller, M., Ferreira, L.G. Regional variations in biomass distribution in savanna woodland in Brazil. Biotropica, in press.
Morton, D.C., DeFries, R.S., Shimabukuro, Y.E., Anderson, L.O., Arai, E., Espirito-Santo, F.d.B., Freitas, R., Morisette, J., 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Procedings of the National Academy of Sciences of the United States of America 103, 14637–14641.
Morton, D.C., Le Page, Y., DeFries, R., Collatz, G.J., Hurtt, G.C., 2013. Understorey fire frequency and the fate of burned forests in southern Amazonia. Philosophical Transactions of the Royal Society B 368, 20120163.
Motta, P.E.F., Curi, N., Franzmeier, D.P., 2002. Relation of soils and geomorphic surfaces in the Brazilian Cerrado. In: Oliveira, P.S., Marquis, R.J. (Eds.), The Cerrados of Brazil: Ecology and natural history of a neotropical savanna. Columbia University Press, Chicago, pp. 13–32.
Nalepa, R.A., Bauer, D.M., 2012. Marginal lands: the role of remote sensing in constructing landscapes for agrofuel development. Journal of Peasant Studies 39, 403–422.
Nefedova, T., 2011. Agricultural land in Russia and its dynamics. Regional Research of Russia 1, 292–295.
Nickerson, C., Ebel, R., Borchers, A., Carriazo, F., 2011. Major Uses of Land in the United States, 2007, EIB-89. U. S. Department of Agriculture, Economic Research Service.
Oliveira, O.C., Oliveira, I.P., Alves, B.J.R., Urquiagas, S., Boddey, R.M., 2004. Chemical and biological indicators of decline/degradation of Brachiaria pastures in the Brazilian Cerrado. Agriculture, Ecosystems, & Environment 103, 289–300.
Olson, D.M., Dinerstein, E., 1998. The Global 200: a representation approach to conserving the Earth's most biologically valuable ecoregions. Conservation Biology 12, 502–515.
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.
Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E., Zhuravleva, I., 2008. Mapping the world's intact forest landscapes by remote sensing. Ecology and Society 13, 51.
Potter, C., Klooster, S., Huete, A.R., Genovese, V., Bustamante, M.C., Ferreira Jr., L.G., Oliveira Jr., R.C., Zepp, R., 2009. Terrestrial carbon sinks in the Brazilian Amazon and Cerrado Region predicted from MODIS Satellite Data and ecosystem modeling. Biogeosciences Discussions 6, 1–23.
Prishchepov, A.V., Radeloff, V.C., Baumann, M., Kuemmerle, T., Müller, D., 2012. Effects of institutional changes on land use: agricultural land abandonment during the transition from state-command to market-driven economics in post-Soviet Eastern Europe. Environmental Research Letters 7, 0204021.
Ramankutty, N., Foley, J.A., Norman, J., McSweeny, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecology and Biogeography 11, 377–392.
Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22, GB1003, http://dx.doi.org/10.1029/2007GB002952.
Sano, E.E., Barcello, A.O., Bezerra, H.S., 2001. Assessing the spatial distribution of cultivated pastures in the Brazilian savanna. Pasturas Tropicales 22, 2–15.
Sano, E.E., Rosa, R., Brito, J.L.S., Ferreira Jr., L.G., 2010. Land cover mapping of the tropical savanna region in Brazil. Environmental Monitoring and Assessment 166, 113–124.
Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kuemmerle, T., Balmann, A. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. Global Biogeochemical Cycles, in review.
Soares-Filho, B.S., Nepstad, D., Curran, L., Voll, E., Cerqueira, G., Garcia, R.A., Ramos, C.A., McDonald, A., Lefebvre, P., Schlesinger, P., 2006. Modeling conservation in the Amazon basin. Nature 440, 520–523.
Sparovek, G., Berndes, G., Klug, I.L.F., Barretto, A.G.O.P., 2010. Brazilian agriculture and environmental legislation: status and future challenges. Environmental Science & Technology 44, 6046–6053.
Vera-Diaz, M.D.C., Kaufmann, R., Nepstad, D., Schlesinger, P., 2008. An interdisciplinary model of soybean yield in the Amazon basin: the climatic, edaphic, and economic determinants. Ecological Economics 65, 420–431.
Verhegghen, A., Mayaux, P., De Wasseige, C., Defourny, P., 2012. Mapping Congo Basin vegetation types from 300 m and 1 km multi-sensor time series for carbon stocks and forest areas estimation. Biogeosciences 9, 5061–5079.
Visser, O., Spoor, W., 2011. Land grabbing in post-Soviet Eurasia: the world's largest agricultural land reserves at stake. Journal of Peasant Studies 38, 299–323.
Vuichard, N., Ciais, P., Belelli, L., Smith, P., Valentini, R., 2008. Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990. Global Biogeochemical Cycles 22, GB4018.
The World Bank, 2010. Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits? The World Bank, Washington, DC.
Young, A., 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. Environment, Development and Sustainability 1, 3–18.
Young, A., 1998. Land Resources: Now and for the Future. Cambridge University Press, Cambridge, UK p. 319.
Young, A., 2000. How much spare land exists? Bulletin of the International Union of Soil Science 97, 51–55.
Zhang, Q., Justice, C., Jiang, M., Brunner, J., Wilkie, D., 2006. A GIS-based assessment on the vulnerability and future extent of the tropical forests of the Congo basin. Environmental Monitoring and Assessment 114, 107–121.