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Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa



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ABSTRACT

Sub-Saharan Africa is typically regarded as land abundant, and previous efforts to estimate the true extent of potentially available cropland (PAC) have largely affirmed this perception. Such efforts, however, have largely focused on production potential and have underemphasized economic profitability and other constraints to expansion. This paper re-estimates PAC for Africa in a more explicit economic framework that emphasizes the returns to agricultural production under a variety of assumptions, using recent geospatial data. Existing PAC estimates for Africa are shown to be highly sensitive to assumptions about land productivity and market access, and are moderately influenced by the use of alternative data sources. The region's underutilized land resources are concentrated in relatively few countries, many of which are fragile states. Between one-half and two-thirds of the region's surplus land is currently under forest cover; conversion of forests to cropland would entail major environmental costs. Most of the continent's unexploited land resources are located far from input and output markets, limiting their economic attractiveness. In the long run, improvements in infrastructure and agricultural productivity and the growth of hinterland towns will enhance the economic returns to cropland expansion. In the short to medium term, however, the potential for profitable smallholder-based cropland expansion in most African countries is likely to be much more limited than it is typically perceived to be.

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Introduction

Sub-Saharan Africa has about 900 million inhabitants at present – a number expected to grow to 1.4 billion by 2030 (UN, 2013). Substantial increases in agricultural output will be required to meet the rising demand for food within the region. Such output growth will have to come from higher yields on existing cropland and/or expansion of land under cultivation. Over the past four decades, crop production growth has occurred predominantly through area expansion (Brink and Eva, 2009; Evenson and Gollin, 2003). While there would be distinct advantages if additional food supplies could be generated mainly through intensification of existing farmland, this may not be realistic. It is almost certain that African governments will face intensified political and economic pressures to allocate much of the region's underutilized land for exploitation, including at the expense of the region's forest land (Gibbs et al.,

2010), to meet the growing food and energy needs of African cities and global markets.

The recent "land grab" phenomenon – driven largely by rising international food and energy prices – has sparked renewed interest in determining the true extent of under-utilized land in Africa. It is well understood that rural Africa is highly heterogeneous and that much of its land is either unutilized or underutilized even while a considerable fraction of its rural population resides in densely settled smallholder farming areas facing land shortages (Table 1; e.g., Tittonell and Giller, 2013; Jayne et al., 2014). Less well understood is how land transfer decisions made today will affect the viability of future agricultural development patterns in the coming decades, particularly the potential for cropland expansion under a smallholder-led development strategy. Unlike other developing regions, Africa's rural population will continue to grow by almost 50% between 2015 and 2050 (UN, 2013).

The demand for unutilized land by indigenous African communities will depend largely on the rate of non-farm employment growth, land productivity growth rates, and on the potential for rural-rural migration to relieve land pressures in densely populated areas. Robust growth in non-farm employment opportunities

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Table	1
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Production costs per hectare (Zambian maize).

Costs (USD/ha)	Small farm	Large farm	
	Low-level management	Medium-level management	High-level management
Labor	215	108	180
Traction	38	75	85
Other costs ^a	9	19	274
Fertilizer	0	213	285
Herbicides and pesticides	0	10	16
Seed	0	47	70
Total costs excluding land	263	473	910

Notes:

Source: ZNFU Enterprise Budgets (ZNFU, 2011). Management levels (low-, medium- and high-levels of inputs) are defined to correspond to the management levels used by the GAEZ, where the low-input "traditional management" assumption is defined as production based on the use of traditional cultivars, labor-intensive techniques, and minimal application of purchased inputs and minimal conservation measures; medium-level corresponds to the intermediate-input "improved management" assumption, wherein partly market oriented production is based on improved varieties, mostly manual labor with some mechanization, some application of fertilizer, herbicides and pesticides, adequate fallows and some conservation measures. See Fischer et al. (2009: p. 38) for more details.

^a Other costs include fuel, oil, crop insurance, packaging, repairs and maintenance.

and in cropland productivity will relieve pressures on the demand for new cropland, but these sources of growth are not assured. It is indeed likely that cropland expansion will be necessary for the success of a smallholder-led development trajectory in much of the region. For this reason, well-designed agricultural development strategies will depend on accurate estimates of the quantity and spatial distribution of underutilized land that is suitable for cropland expansion, or more accurately the relationship between food and input prices and the quantity of land available for profitable cropland expansion (Hertel, 2011).

In a widely cited report, Deininger and Byerlee (2011) estimate the potential for cropland expansion in Africa using geospatial data on population distributions and agroecological potential. This important contribution bases its conclusions on a relatively simple methodology combining various thresholds of agronomic suitability, existing rural population densities, and proximity to cities. A striking conclusion of that analysis was that Africa has more underutilized arable land than any other continent: 198–446 million hectares, depending on the assumptions used, and that there is likely to be ample room for well-planned large-scale land acquisitions to contribute to the region's economic growth without compromising land accessibility for indigenous communities.

This study revisits the question of how much land is really available for crop expansion in Africa, employing explicit economic criteria. Because the incentives for crop area expansion clearly depend on agricultural input and output price levels and ecological and social costs associated with land expansion, we agree with Hertel (2011) and Lambin et al. (2013) in posing the question as a function of such variables. We therefore report alternative estimates of potential area for cropland expansion (PAC) for various scenarios based on alternative assumptions to be explained below.¹ We also address the related question of what kinds of factors might substantially constrain cropland expansion and/or rural-to-rural migration.

The motivations for this research are twofold. First, more accurate estimates of PAC can guide policy decisions about future land allocation. For example, if it were concluded that there is great potential for PAC, this would relieve the opportunity costs of allocating substantial amounts of land to foreign interests that might otherwise entail foreclosing indigenous communities' access to additional land. By contrast, findings of limited potential for PAC would create a greater sense of urgency in resolving how remaining scarce underutilized land should be allocated among competing interest groups.

Second, the relative endowments of land and labor will be crucial for a country's agricultural development path (Boserup, 1965; Ruthenberg, 1980; Ruttan and Havami, 1984). Land constrained rural populations clearly need to focus their efforts on agricultural intensification, as well as nonfarm diversification and reducing population growth (Headey and Jayne, 2014). But populations with ample land resources of sufficiently good quality will typically resist intensive technologies since land expansion and fallowing are far less costly than intensive agricultural practices (Binswanger and Pingali, 1988). For African countries endowed with ample underutilized land it is not obvious that the technological priority for their farming systems should be increasing yields on existing land resources. Rather, it may well be road expansion, or agricultural technologies, that increase the returns to underutilized land resources.² Assessing the economic potential for land expansion could enable national and international agricultural research systems to anticipate desired technical crop production trajectories based on relative factor scarcities, and help policy makers prioritize public expenditures that take account of these emerging factor scarcities.

The remainder of this paper is structured as follows. Section 'Prior studies estimating surplus land' reviews prior studies concerned with estimating PAC in Africa. Section 'Analytical framework' describes the methodological underpinnings of our model. Section 'Data and assumptions' describes the data and key assumptions. Section 'The magnitude and location of potential available cropland in Sub-Saharan Africa' presents our basic estimates of the magnitude and location of potentially available cropland, including an assessment of the economic returns to expansion into currently underutilized areas. We evaluate the sensitivity of our estimates in Section 'Alternative future scenarios for prices and productivity', and entertain plausible future price and technology scenarios in Section 'Other constraints to expansion'. Section 'Conclusions and policy implications' examines important non-economic constraints to utilizing currently uncultivated land. We conclude by outlining the implications of our findings for policy and offer suggestions for further empirical assessments.

¹ This study defines PAC in the same way as Lambin et al. (2013), i.e., the reserve of moderately to highly productive land that could be utilized for rainfed farming, that is not currently under intensive use or legally protected. Our only departure from Lambin et al. is that several of our scenarios explicitly include land under mature forest cover in order to measure the sensitivity of PAC estimates to the inclusion of forest land.

² The Brazilian *cerrado*, for example, was opened up by a combination of road expansion and agricultural R&D aimed at increasing the productivity of tropical soils (The Economist, 2010).

Prior studies estimating surplus land

The magnitude of land available for cropland expansion is still not well established, despite the large number of estimates produced over the last decade (FAO 1981, 1984; Alexandratos, 1995; Luyten, 1995; Fischer and Heilig, 1998; Ramankutty et al., 2002; Cassman and Wood, 2005; Fischer and Shah, 2010 (utilized by Deininger and Byerlee, 2011), Alexandratos and Bruinsma, 2012; Lambin et al., 2013). The key point is that estimates of potentially available cropland (PAC) are very sensitive to assumptions about what constitutes "potentially available" (and to a lesser extent on data sources). There seems to be a consensus that arable land is abundant in the region as a whole, although exactly how much of this stock is utilizable (and by whom) is far from clear. Many estimates have emphasized the production potential of land, drawing on georeferenced data on land and climate characteristics and associated biophysical production characteristics (e.g. FAO, 1981, 1984; Alexandratos, 1995; Luyten, 1995; Fischer and Heilig, 1998; Fischer and Shah, 2010; Alexandratos and Bruinsma, 2012).³ Estimates of the stock of PAC from these estimates for SSA have ranged from 400 to more than 800 million hectares.

Young (1999, 2000, 2005) has been a vocal critic of such estimates, noting that they simply do not conform with many of the empirical regularities of smallholder agriculture in the region.

"If there is so much spare land, why has cultivation been so widely extended onto steep slopes, onto extremely infertile soils, and into semi-arid zones liable to frequent crop failure'? Why is there so much illegal incursion into forest reserves and national parks? Why has average farm size in some countries fallen below one hectare, and why are infertile soils which need rest periods cropped continuously? Why is there so much land degradation, widely attributed to the interaction of land shortage with population increase and poverty? Above all, if it were possible to bring further land under cultivation, why do 800 million people suffer from endemic undernutrition? Inequitable land distribution is certainly part of the answer, but these indicators are so widespread as to suggest that in many regions, the supply of available land is approaching zero"

[Young (2000: 51).]

On the basis of these observations, Young suggests that there is a systematic combination of overestimation of cultivable land, underestimation of land already cultivated, and/or underestimation of competing non-agricultural land uses.

Lambin et al. (2013) similarly attempt to tone down the enthusiasm of earlier estimates by noting that a wide range of constraints and tradeoffs are typically left out of such accounting methods. They employ a "bottom up" approach to identify a number of social, administrative, economic and physical constraints to conversion of potential croplands. They conclude that there is "substantially less potential additional cropland than is generally assumed once constraints and trade-offs are taken into account" (p. 892).

Finally, while Deininger and Byerlee's (2011) estimates of PAC raise vitally important questions for the region's future development, the relative simplicity of their analytical framework warrants a number of important extensions. In particular, their study uses quite simple thresholds to identify underused land resources with some economic potential: agronomic suitability for crop production, rural population densities below 25 km²; land that is currently uncultivated and located within 6 h travel time to a city of 20,000 or more inhabitants. Several fundamental policy questions

³ Young (2005) notes that most of these studies draw on the same source information, i.e. what is now codified as IASA/FAO's GAEZ database, although the current version has certainly evolved from earlier incarnations.

can be informed by understanding how sensitive PAC estimates are to these assumptions and by imposing explicit economic criteria in the analysis.

This study aims to develop a more economically realistic assessment of crop land expansion potential in Sub-Saharan Africa. Ultimately, such an assessment would engage with the desirability of land expansion from the farmer's perspective, i.e. as a function of: (1) bio-physical and agro-ecological factors; (2) output prices, input costs, and transport costs; (3) the influence of disease and conflict on settlement patterns; (4) the costs farmers face in preparing land for cultivation;⁴ and (5) the strength of institutions and policies to protect local communities' land rights.⁵ While data limitations preclude us from addressing all of these factors, we do have information that enables us to take better account of spatially varying economic factors than has typically been the case in PAC assessments in the past. We use a spatially-explicit profitability framework to explore a pair of key policy questions. First, what is the potential for cropland expansion in Africa in the short to medium term, i.e. given current infrastructure and productivity levels in the region? Second, what is the potential in the long run once these constraints have been overcome?

Analytical framework

The potential for land expansion in Sub-Saharan Africa (SSA) is based on a combination of biophysical and economic factors. Our approach involves, first, defining the geographical scope of potential expansion, i.e. identification of areas not currently under agricultural production; and second, incorporating estimates of biophysical production potential, along with conservative assumptions about profitability, to characterize the economic attractiveness of expansion within these candidate areas.

Defining the envelope of potentially available cropland

Following Lambin et al. (2013), we refer to the stock of underutilized land resources as *potentially available cropland* (PAC). This is defined as land that is not currently cultivated, not forested, not part of National Park systems or other gazetted areas, and which currently has very low rural population densities. Within these areas, we then evaluate the feasibility of use.

Estimating the economic returns to expansion

Our analysis of the economic returns to expansion is based on a net potential revenue calculation, similar to the approach taken by You et al. (2011) in their study of African irrigation potential. Our basic approach is as follows. We first divide the region into grid cells of roughly 9 km² (the data are described in detail in the next section). Within each grid cell, we jointly evaluate the returns to 9 major crops produced under rainfed conditions using low or medium input levels, and derive estimates of aggregate net revenue for a production portfolio consisting of the three most profitable crops. We then evaluate the profitability of expansion into currently uncultivated land in terms of gross margins:

⁴ Here we refer to the direct costs of conversion borne by would-be cultivators, e.g. cost of clearing forests, cost of cultivating land prone to waterlogging. There are also, of course, significant indirect or social costs associated with land conversion. For example, the conversion of forest to cropland implies externalities in the form of loss of timber and other forest resources, the loss of habitat for forest-dwelling fauna, the loss of ecosystem services provided by forests, etc.

⁵ In addition to desirability, assessments should also address availability constraints: e.g. the extent to which local land resources are not available for cultivation due to their designation as a protected area, mining or logging concession, military grounds, or other territory.

(Gross revenue - variable production costs)/hectares cultivated

We operationalize this as:

[Yield (MT/ha) * output price(\$/MT)]

– variable production costs(\$/ha)

which is calculated on an array of parameters defined for each grid cell.

This approach synthesizes two important spatially-varying elements of production profitability: *land productivity* (i.e. the biophysical production endowment), and the relative *prices of inputs and outputs*. These elements, which vary from location to location, jointly determine the profitability of agricultural production under any given set of assumptions about production technology.

Land productivity enters into the accounting through the potential yield estimates, taken from the GAEZ 3.0 database. Costs and revenue assumptions rely on grid cell-specific prices of inputs and outputs, calculated on the basis of prevailing market prices and the distance of each grid cell to the nearest market. Data and method details are provided in the next section. Together, these measures allow us to calculate the returns to expansion in per hectare terms. Our basic economic criterion is that candidate areas must be capable of generating at least \$250 USD/ha. This requirement is very modest. Given that most farmers have 2 hectares or less, the \$250 net revenue criterion implies that the minimum net revenue is \$500 per year per household in order to consider that grid-cell as containing sufficiently suitable land for crop production. This is an exceedingly small number, far below the \$1.25 a day poverty line for a household of 5 members.⁶

Data and assumptions

Continued discrepancies in land cover maps

Despite the rapid expansion of satellite imagery and other remote sensing information in recent years, there remains a lack of consistent and reliable data on the location and area intensity of land cultivation (Fritz et al., 2011). This is important for analyses such as ours, since our ability to make statements about where land could be brought into cultivation is linked with our ability to say something about where land is currently being cultivated.

Analysis of currently available global and regional land cover datasets indicate very high levels of disagreement in both the forest and agricultural domains (e.g., Fritz and See, 2005, 2006, 2008; Herold et al., 2008; Fritz et al., 2010, 2011; Kaptué Tchuenté et al., 2011; Pérez-Hoyos et al., 2012).⁷ This is especially true in areas of high landscape heterogeneity or fragmentation, which is a defining feature of smallholder production landscapes, especially in extensive systems.

Appendix Table A1 presents the country-level estimates of currently cultivated and forested areas from the GAEZ, GlobCover and MODIS datasets (described below). We show these alternative estimates to emphasize the uncertainty inherent in land cover datasets and, consequently, the sensitivity of conclusions to the choice of dataset (Fritz et al., 2011). Generally, speaking, we observe that the GAEZ and GlobCover estimates of current crop cultivation are roughly the same across the region. The GAEZ total for SSA is about 5% more than the more recent GlobCover estimates. The estimates of forest cover, on the other hand, are quite different: the GAEZ total for the region is about 20% less than the estimated area from GlobCover. This indicates that one possible source of upward bias in Deininger and Byerlee's (2011) estimates of surplus land (which uses land cover data from the GAEZ) may simply be an artifact of the choice of input data, which in their case may underrepresent land under forest cover in SSA.

The spatial distribution of land and people in SSA

This study utilizes land cover information derived from remote sensing data, to characterize the current extent of cultivated area and forest land. Our land cover data come from three sources: the data compiled (from other sources) within the GAEZ 3.0 database (Fischer et al., 2009), and more recent and higher resolution information on land cover from GlobCover for 2009 (Bontemps et al., 2011) and Modis v.5 for 2010 (Friedl et al., 2010). In acknowledgement of the continued uncertainty in satellite-based land cover classifications (Herold et al., 2008; Fritz and See, 2008; Fritz et al., 2010, 2011; Kaptué Tchuenté et al., 2011; Pérez-Hoyos et al., 2012), we evaluated the degree of correspondence between these datasets (see Chamberlin, 2014, for details). Like similar investigations, we found widespread disagreement in these datasets, particularly for forest cover. Our approach to resolving this uncertainty was to average across the three datasets to attain an estimate that may be more reasonable than any single dataset.⁸

We supplement our land cover information with several other key spatial datasets. Rural population distributions come from the AfriPop dataset for 2010 (Linard et al., 2011). Data on protected areas are from IUCN/UNEP (2009). Urban extents were defined using data from a variety of sources, including the GRUMP dataset (Balk and Yetman, 2004), and GlobCover. Our spatial analysis aggregates up from the native resolution of all input datasets to a uniform gridded analysis environment (i.e., a set of grid cells) of 5 decimal minutes (about 9 km²). We do this principally in order to facilitate linkage with the GAEZ 3.0 database, which is defined at that level of spatial resolution.

Potential yield estimates

To define the production potential of different areas, we use data on crop-specific land suitability and potential yield data from the GAEZ 3.0 database (IIASA/FAO, 2012). Suitability is conditioned by climatological conditions as well as slope, drainage and other soil and terrain characteristics (Fischer et al., 2000).

The GAEZ defines agroclimatically attainable yields on the basis of biophysical endowments (such as rainfall, temperature, terrain and soil characteristics) which are embedded within the GAEZ database, as well as assumptions about input management levels and irrigation (Fischer et al., 2000). Three management levels are defined in the dataset: low, medium and high, where the low level corresponds to subsistence agriculture and minimal use of modern inputs, while the high level corresponds to commercially oriented production with commensurately high levels of modern input use.⁹

Our analysis estimates net revenue per hectare for 9 major crops (wheat, rice, maize, barley, sorghum, banana, soybean, coffee and cotton) produced under rainfed conditions, and uses the mean

⁶ We do note that US\$250 per hectare may provide sufficient gross margins to be viable for large farming operations. However, the size at which gross farm revenue might justify expansion is beyond the scope of our study. Nonetheless, the fact that larger farms may be viable at lower per hectare margins does suggest that the economic viability of land expansion may depend, in part, on future changes in farm structure.

⁷ Many studies find good overall agreement, in terms of aggregate numbers, but high disagreement in individual land classes and/or their spatial coincidence

⁸ In practice, interestingly, we find that differences in estimates of cropland and forested area do not generally have large impacts on the PAC estimates which we report below. This probably has most to do with the high degree of concentration of underutilized land within a few countries, as we describe later in the paper. Analyses conducted at higher spatial resolution and/or for smaller study areas may be much more sensitive to dataset choice.

⁹ See IIASA/FAO 2012, p. 38, for a description of the input management regime assumptions.

of the three most profitable crops to derive gross margins for each grid cell.¹⁰ These gross margins are estimated for both medium and high management scenarios, though this article focuses mainly on findings from the medium input conditions which are more characteristic of semi-commercialized smallholder production.¹¹ Although the attainable yield estimates provided by the GAEZ distill a great number of complex parameters and provide a remarkably useful tool for spatially-explicit analysis, they suggest potential yields that greatly exceed smallholder yields as observed in survey data, a "yield gap" that Deininger and Byerlee (2011) discuss at length. Our work uses observed yields for Zambian maize production as the basis for down-scaling the agro-climatically attainable yield estimates to more realistic values. Using district averages, we find that smallholders obtain roughly 30-40% of the corresponding estimated attainable yields (for low- and medium-level management).¹² Although data are more limited for large African farms, we assume that commercial farmers are obtaining 60% of obtainable vields under high-management conditions. These assumptions may be seen as generous given the findings of others on yield gaps in the region; Deininger and Byerlee (2011), for example, report that cereal yield gaps for Africa as a whole are about 80%. We use these assumptions to define scaling factors for the GAEZ yield estimates, such that the potential yields assumed for uncultivated land are more in line with what the region's farmers actually obtain.

Spatially varying output prices

Previous assessments of cropland expansion potential held output prices constant across space (You et al., 2011; Deininger and Byerlee, 2011). In this study, we generate spatially explicit prices using stylized assumptions about transfer costs over distance gradients. First, we assume that food prices in the region's major markets are equivalent to 1.2 times global wholesale prices, reflecting the import parity conditions that most African cities face for food commodities.¹³ Wholesale prices on our 9 commodities are from World Bank Commodity Price Data (a.k.a. Pink Sheet) for the year 2010. For each crop, we then estimate farmgate producer prices as a distance decay function of the form

$$P_i^{farmgate} = P_i^{market} \cdot (1 - \exp(-\alpha/d_{ii})\gamma)$$

where $P_i^{fammgate}$ represents the producer price in continuous space and d_{ij} is the distance (measured here as travel time) from each location *i* to the nearest major market *j*, α is a parameter that governs the extent of price decay, and γ defines the maximum price decay over space. Although this decay function is somewhat arbitrary in its specific form, it possesses several desirable properties: the estimated producer prices vary over space in ways which are broadly consistent with theory and existing empirical evidence (e.g. Minten, 1999); the spatial price decay is relatively gradual, and parameters are defined such that the farm-gate price in the



Fig. 1. Per hectare production costs over economic space, for low, medium and high-level production management conditions.

most remote areas is not less than 70% of the import parity price in the nearest regional market.

Production costs

Ideally, our Africa-wide estimates should be informed by a broad array of data on production costs from different agroecological settings. However, in the absence of such comprehensive information, we rely on data from Burke et al.'s (2011) detailed study of smallholder maize production costs in Zambia, using nationally representative data collected by the Government of Zambia's Ministry of Agriculture, along with representative farm budgets for commercial and smallholder production in Zambia (ZNFU, 2011). We characterize production costs per hectare on the basis of observed costs for two groups of smallholders - low-level managers, who rely predominantly on family labor and other non-purchased inputs, and medium-level managers, who use moderate amounts of fertilizers (100-200 kg/ha of a standard NPK mixture) and other modern purchased inputs - as well as for large commercial farmers, who are assumed to use high-levels of inputs. These estimates of production costs are compared with other available estimates in the region, including representative farm budgets derived for AgriBenchmark by the Regional Network of Agricultural Policy Institutes of Eastern and Southern Africa, and found to correspond reasonably closely. For example, available estimates of maize production costs per hectare planted for low and medium management conditions converge fairly closely around our estimates of US\$263 and \$473, respectively.

Furthermore, we assume that the costs of purchased inputs (such as fertilizer) increase with distance from markets. Distance-mediated input costs are modeled as a simple exponential function of hours of travel time to the nearest urban center of 100,000 or more inhabitants, whereby the effective price of a purchased input at a farm located 15 h from the market is about a third higher than the market price.¹⁴

The basic cost assumptions for the alternative management levels are shown in Table 1 (where distance from market is equal to zero). As market distance increases, the cost of purchased inputs rises (for the medium-level and high-level managers who use such inputs) and therefore the total cost of production under the two management levels diverges as shown in Fig. 1.

Under this setup, potential net revenue is a function of both biophysical potential (via yields) as well as economic remoteness (via prices and costs). Thus, in very remote locations we would expect

¹⁰ These 9 crops were selected because they represent because of available price data and the fact that they are present in typical production portfolios across a diversity of farming systems. We do acknowledge, however, that land expansion may be driven significantly by other, commercial crops which may offer relatively high returns in currently forested, less accessible areas. For example, oil palm, rubber and sugarcane have all been implicated in forest conversion in Asia. By omitting these, we may be underestimating potential returns to expansion.

¹¹ Our analysis emphasizes rainfed production under modest levels of purchased inputs because most current smallholder production takes place under these conditions, and farmers in isolated and land abundant conditions (where expansion may take place) are unlikely to employ intensive technologies.

¹² Appendix Table A2 compares potential and actual yields for maize in Zambia.

¹³ To the extent that selected agricultural commodity prices are lower than this, our analysis may somewhat overestimate the true potential for profitable cropland expansion.

¹⁴ This relationship broadly corresponds with the authors' analysis of farm gate fertilizer prices observations in household survey data from the region, as well as other studies of input price formation in the region, e.g. Tchale and Keyser (2010).

Table 2

Assumptions underlying alternative estimates of potentially available cropland.

Criteria	(1) Suitable for cropland expansion (2) Profitable for cropland expansion						
Cultivated area	Only grid cells currently designated as "uncultivated" are candidates for potential cropland expansion						
Forested area Rural density	Only non-forested portion of grid cell are candidates Only sparsely populated areas (<25 persons/square kilometer) ar	ion-forested portion of grid cell are candidates for potential cropland expansion ulated areas (<25 persons/square kilometer) are candidates for potential cropland expansion					
Desirability Agronomic potential Returns to cultivation	Potential yields are at least 45% of the maximum attainable yield for at least one of maize, wheat, soy, sugarcane, or oil palm ^a NA	(Enters via productivity assumptions below) Gross Margins > threshold USD/ha/year(based on realistically					

Notes:

^a The GAEZ defines a suitability index (SI) as the share of pixel-specific agronomically attainable yield relative to the maximum attainable yield for a given production technology regime (i.e. level of inputs and type of water management; see Tóth et al., 2012 and Fischer et al., 2009). Fischer and Shah (2011) defined a threshold SI value of 60 as a suitability criterion; we were not able to replicate their estimates using this value and therefore use a value of 45 here to better approximate the magnitude of their estimates as a baseline.

^b The GAEZ calls potential yield "agroclimatically attainable yield". Attainable share of potential yield is defined by scaling parameter α = .40/.40/.60 for (low/medium/high) input management assumptions, respectively. See methods section for more details on assumptions and parameter definitions.

that only relatively productive areas are able to generate positive net revenue to expansion. While there is certainly some arbitrariness in this formulation, we emphasize that (a) our assumptions are anchored in empirical evidence of smallholder net revenue, and (b) as stylized as they are, these assumptions are more realistic than assumptions of constant costs across space, or, worse still, no production costs at all.¹⁵

Costs of land conversion

Many assessments of the economic potential for crop land expansion focus on the relative returns to alternative uses without accounting for initial land conversion costs (e.g. Dejene et al., 2013). However, the costs associated bringing new land under cultivation may be considerable in heavily forested, steeply sloped, or waterlogged areas, for example. Areas of high disease burden and civil conflict impose additional costs and risks of cropland expansion. Perhaps more important are the costs of land conversion borne by the broader society, including costs associated with the release of greenhouse gases into the atmosphere and consequent changes in the environment (Powlson et al., 2011). Because these costs are largely unknown, we do not account for these land conversion costs but emphasize that by ignoring them, our estimates are likely to overstate the true extent of profitable land expansion opportunities.

The magnitude and location of potential available cropland in Sub-Saharan Africa

Table 2 summarizes the basic sets of assumptions used to identify the extent of PAC in the region. We use two alternative sets of criteria for identification of PAC. As a baseline reference (column 1), we follow Deininger and Byerlee (2011) and others in defining suitability on the basis of production potential. Furthermore, and again following the Deininger and Byerlee study, we require that candidate areas be non-cultivated, non-forested, not protected and have population densities below 25 persons per km². We later relax these assumptions and show the sensitivity of PAC potential to alternative assumptions. Column 2 summarizes our basic economic criteria for expansion potential, as outlined in the methods section. We maintain the criteria of non-cultivated, non-forested, not protected and low-density areas, but rather than relying on a biophysical suitability threshold, we impose a minimum profitability criterion which reflects different levels of crop-specific production potential as well as the spatially varying costs and returns to production. Assuming realistically attainable shares of the estimated potential yields under low-input management, we impose a minimum gross margins requirement of 250 USD/ha/year. Recall our working assumption that gross margins values of less than 250 are probably insufficient to rationally justify expansion.

Table 3 presents the resulting estimates of the amount of underutilized land by country and sub-region. The first column shows the PAC estimates resulting from applying the suitability criterion and the subsequent columns show the profitability criterion under the assumption of medium-input levels (characteristic of semi-commercialized smallholders) and high-input levels (characteristic of larger commercial farms), respectively.¹⁶

The countries with the largest amounts of underutilized land are Sudan,¹⁷ Madagascar, DRC, Mozambique, Angola, Congo Republic, CAR, Ethiopia and Zambia, which together account for about 65% of all the land available for cropland expansion in Sub-Saharan Africa. This is very consistent with the results of other studies. When we move from the suitability criteria to the profitability criteria, we see that, under the smallholder expansion scenario, the PAC decreases by about 70% to 80 Mha. When we move to the commercial farm production assumptions, we see a decrease in the PAC estimate from the suitability baseline by a lesser amount, declining by 32% to 167 Mha.

In recent decades, the expansion of agricultural area in SSA has largely been at the expense of forest cover (Brink and Eva, 2009; DeFries et al. 2010; Gibbs et al., 2010). Recognizing that such conversion is likely to characterize further expansion suggests that a more realistic assessment of expansion potential will not exclude all land that is currently under forest cover, despite the high environmental costs associated with the loss of forest resources. The middle columns of Table 3 show the PAC estimates resulting from the same set of criteria used earlier, except for now we allow land which is currently forested to be converted to crop production. Unsurprisingly, the total PAC estimates increase dramatically when we allow such conversion: the baseline PAC estimate

¹⁵ For concreteness, consider previous treatments of potential revenue. Deininger and Byerlee (2011) assume that output prices are constant across space and make no assumptions about production costs at all other than by excluding areas further than 6 h travel time from a town of 20,000 or more as too remote to be profitable. You et al. (2011) assume that output prices are constant across space and model production costs as a fixed share of gross revenue (set at 70% for all commodities). In both of these treatments, the only spatially varying parameter to profitability is potential yield, which is taken directly from the GAEZ.

 $^{^{16}}$ We also calculated profitability for subsistence/low-input production, but have not shown this in Table 3 for reasons of space.

¹⁷ In this study, we use the old definition of Sudan, i.e. the area now corresponding to both Sudan and South Sudan.

Table 3

Estimates of potentially available cropland (1000s of hectares).

Country	Excluding	Excluding forest land			Including forest land			Forested % of PAC		
	Suitable	Profitable		Suitable	Suitable Profitable			Profitable		
		Medium management	High management		Medium management	High management		Medium management	High management	
Angola Cameroon CAR Chad Congo-Brazz. DRC Ethiopia Ghana Guinea Ivory Coast Kenya	18,700 5488 8520 12,600 3292 33,300 4716 3555 3749 3415 4458	1644 5267 10,300 561 6788 23,800 3 558 1685 2221 301	8472 8357 18,200 6919 7166 31,400 1114 1903 8245 5096 998	32,600 17,300 13,900 15,600 16,900 130,000 5817 4530 5201 5557 5175	3617 21,400 20,000 561 21,600 111,000 8 814 3070 4251 334	17,400 26,600 33,600 8279 25,300 132,000 1492 2473 11,700 8790 1144	43% 68% 39% 19% 81% 74% 19% 22% 28% 39% 14%	55% 75% 49% 6% 69% 79% 56% 31% 45% 48% 10%	51% 69% 46% 72% 76% 25% 23% 30% 42% 13%	
Madagascar Mozambique South Africa Sudan Tanzania Zambia Zimbabwe	16,300 21,400 4577 41,900 16,100 25,500 5736	13,100 4258 95 2306 1598 0 97	19,100 10,500 1992 9874 4937 3349 4643	18,300 33,300 5116 50,000 22,900 42,100 7032	15,600 7399 137 3305 2559 0 157	22,500 17,200 2424 13,400 7381 5056 5861	14% 11% 36% 11% 16% 30% 39% 18%	16% 16% 42% 30% 30% 38% 0 38%	15% 39% 18% 26% 33% 34% 21%	
East/Central Southern West SSA	125,658 93,975 27,719 247,352	46,310 19,205 14,581 80,096	81,710 48,137 37,207 167,054	261,306 140,574 53,978 455,859	160,232 26,931 55,237 242,400	224,045 70,586 89,304 383,935	52% 33% 49% 46%	71% 29% 74% 67%	64% 32% 58% 56%	

Notes: all values are in 1000s of hectares. Countries shown are those for which baseline estimates of PAC excluding forest land exceed three million hectares. The full set of country calculations is available upon request. Columns for "medium management" and "high management" correspond to medium-input levels (characteristic of semi-commercialized smallholders) and high-input levels (characteristic of larger commercial farms). Sudan refers to the old country boundaries, i.e. corresponds to the area within present-day Sudan and South Sudan.

increases from 247 Mha (million hectares) to 473 Mha when forest conversion is allowed, almost doubling in magnitude. Unsurprisingly, the land expansion potential of heavily forested places such as DRC, Angola, Cameroon and Ivory Coast are most sensitive to relaxing the forest restriction. The right hand side of Table 3 reports the proportion of underutilized land available for cropland expansion that is currently under forest cover.

Nonetheless, under the forest expansion scenario, moving from the suitability to the profitability criteria results in very large reductions of PAC estimates under the forest expansion scenarios. The PAC under medium-input profitability criteria is about half that of the estimates based on non-economic "agroecological suitability" criterion (242 Mha versus 455 Mha). The reduction in PAC based on high-input profitability criteria is less drastic (384 Mha versus 455 Mha), but still amounts to a 20% reduction from the non-economic baseline estimate.

This suggests that much of the heavily forested land in Sub-Saharan Africa would not provide profitable opportunities for crop cultivation without major reductions in transport costs and infrastructural improvements.¹⁸ Moreover, the substantial costs of draining large swathes of waterlogged forested area (particularly in the Congo basin) would further constrain land expansion in these countries.

It is possible that our estimates of PAC are sensitive to our selection of economic parameters. One way of exploring this sensitivity is to compute how PAC estimates change as a continuous function of minimum profitability requirements. We graph this sensitivity in Fig. 2. It is readily apparent that, under the assumptions we have outlined above, imposing incrementally higher profitability requirements very quickly reduces the estimated stock of economically viable surplus land in Sub-Saharan Africa. For example, under existing infrastructural and output/input pricing conditions, relatively little surplus non-forested land resources are accessible to cultivators who aspire to generating more than our minimum threshold of USD 250/hectare/year. It is quite likely that previous estimates of PAC based solely on non-economic agroecological suitability criteria are significantly overestimated unless output prices and market access conditions become more favorable.

Allowing for cropland expansion into higher density areas

Deininger and Byerlee's (2011) estimates of PAC considered that land more densely populated than 25 persons per square kilometer was considered unavailable for cropland expansion. We would like to understand how sensitive estimates of PAC in Africa are to alternative population density thresholds. Areas with moderate rural population densities arguably could provide better potential for crop land expansion, e.g. because of more readily available labor. However, the higher the current population density, the more likely that non-displacing cropland expansion could only occur within smallholder modes of crop production. Large-scale and capital-intensive farming approaches might imply substantial land eviction in areas that are already moderately settled. Still, to better understand the severity of these trade-offs, we generate PAC estimates for a wide range of population density thresholds, using the same set of economic criteria specified in Table 2. The relationship between density threshold and PAC is shown in Fig. 3.

Raising the threshold from 25 to 50 persons per km² naturally results in an expansion of PAC, from 80 Mha to 107 Mha excluding forest, and from 242 Mha to 297 Mha when forest conversion is allowed. As the density threshold rises, the increase in PAC is fairly gradual in Western and Southern Africa, but much larger in Eastern and Central Africa (Fig. 3). Still, the gains taper off quickly: going from 25 to 50 persons/km² increases the PAC estimate by about 33%; going from 50 to 75 adds only another 13%.

¹⁸ We note that there is some circularity to this proposition: virgin forests tend to be remote because they are virgin, i.e. clearing such areas goes hand in hand with the development of access roads.





Panel (b): SSA PAC estimates for different farm/management types







Fig. 2. Sensitivity of PAC estimates to minimum gross margins criterion. *Note*: PAC area estimates are based on the profitability criterion and disallow forest conversion, as shown in Table 3, columns 2 and 3. (We also show profitability for low-input assumptions, which are not reported in Table 3.) Criteria other than gross margins are held constant at values described in Table 2.

Market access conditions and the scope for cropland expansion

Clearly our estimates of PAC depend on profitability assumptions. Given our emphasis on spatially varying prices as a function of current market access conditions, it is worth parsing the spatial components of profitability a bit. To begin with, we examine how PAC estimates based on suitability criteria are distributed across space with respect to market access. Table 4 shows the percentages of PAC (defined as agronomically "suitable") in different categories of remoteness, as measured by travel time to the nearest town of 50,000 or more inhabitants. Between a quarter and a third of the total suitable area is further than 12 h from a market of this size, indicating that remoteness plays a substantial role in the profitability story being portrayed here. For the major repositories of PAC, the average levels of remoteness tend to be even higher. Over time, the growth of hinterland towns may fundamentally alter PAC conditions in areas where market access conditions currently constrain the scope for profitable crop production. However, for at least the next decade, poor market access conditions are likely to rule out major swaths of otherwise suitable land from agricultural expansion without major investments in transport infrastructure.

Alternative future scenarios for prices and productivity

The assumptions we have made thus far are based on, *inter alia*, current prices, access conditions, and population density and profitability thresholds. Current conditions, of course, are subject to change: changes in global food market may alter price conditions, new technologies and/or management practices may be widely adopted, etc. This section explores two major scenarios:

- 1. Output prices what happens as world commodity prices rise?
- 2. Production efficiency what happens if farmers are able to narrow the gap between potential and actual yields?

Changes in output prices

Given the recent rise in world commodity prices and more globalized African food markets, we explore how a higher equilibrium output prices would affect PAC, holding everything else constant. Results of sensitivity analysis, shown in Fig. 4, indicate that PAC estimates are quite sensitive to such changes, as we would expect given what we have already seen regarding the importance of profitability on PAC estimates. An increase in output prices by 20% results in an overall PAC increase of 49%; a 40% price increase results in an overall PAC increase of 138% (under the mediummanagement assumption). Regionally, the biggest absolute changes are seen in East/Central (where most underutilized land is found), although the biggest relative changes are in Southern Africa, where a 20% increase in output prices results in a 72% increase in the PAC estimate. Higher prices would thus greatly expand potential crop area in Africa, although we note that a 20% increase above 2010 levels is well above the forecast international prices estimated for the next 10 years by the OECD-FAO (2013).

Changes in production efficiency

A major assumption in our analysis is the attainable share of potential yield estimates. As explained above, we scale the GAEZ estimates to obtain realistic yield levels which are more in line with what we observe in household survey data. However, recog-





Note: PAC area estimates are based on suitability criterion and allow forest conversion, as shown in Table 3, column 4. Criteria other than allowable population density are held constant at values described in Table 2.

Fig. 3. Sensitivity of estimates to population density threshold criterion. *Note*: PAC area estimates are based on the profitability criterion and disallow forest conversion, as shown in Table 3, columns 2 and 3. Criteria other than allowable population density are held constant at values described in Table 2.

 Table 4

 Agronomically suitable land area shares in different remoteness categories.

Countries	Forest exclu	Forest excluded					Forest included					
	1000s ha	0–3 h	3-6 h	6–9 h	9–12 h	>12 h	1000s ha	0–3 h	3–6 h	6–9 h	9–12 h	>12 h
Angola	18,700	5%	18%	18%	18%	41%	32,600	4%	16%	19%	20%	41%
Cameroon	5488	20%	47%	19%	8%	6%	17,300	15%	41%	20%	9%	15%
CAR	8520	3%	14%	21%	23%	40%	13,900	3%	15%	21%	22%	39%
Chad	12,600	9%	29%	28%	14%	21%	15,600	9%	28%	27%	14%	22%
Congo-Brazz.	3292	3%	8%	13%	21%	56%	16,900	1%	2%	6%	13%	78%
DRC	33,300	6%	28%	28%	17%	21%	130,000	4%	20%	24%	17%	35%
Ethiopia	4716	0%	7%	25%	19%	48%	5817	0%	7%	25%	19%	50%
Ghana	3555	23%	41%	19%	11%	5%	4530	23%	41%	19%	11%	5%
Guinea	3749	35%	52%	10%	2%	1%	5201	32%	53%	11%	2%	2%
Ivory Coast	3415	16%	57%	19%	5%	3%	5557	14%	55%	20%	5%	6%
Kenya	4458	5%	33%	31%	14%	17%	5175	4%	32%	31%	15%	18%
Madagascar	16,300	4%	37%	38%	16%	5%	18,300	4%	36%	38%	16%	5%
Mozambique	21,400	4%	18%	22%	17%	40%	33,300	4%	18%	22%	17%	39%
South Africa	4577	49%	41%	8%	2%	0%	5116	48%	42%	8%	2%	0%
Sudan	41,900	10%	31%	22%	14%	23%	50,000	11%	31%	22%	14%	23%
Tanzania	16,100	5%	25%	23%	16%	31%	22,900	5%	23%	23%	16%	33%
Zambia	25,500	7%	20%	20%	19%	34%	42,100	6%	18%	21%	19%	35%
Zimbabwe	5736	33%	52%	12%	3%	1%	7032	34%	51%	12%	3%	1%
East/Central	125,658	7%	27%	25%	16%	26%	261,306	5%	21%	22%	16%	35%
Southern	93,975	9%	25%	22%	16%	28%	140,574	8%	23%	22%	17%	31%
West	27,719	22%	49%	18%	7%	5%	53,978	17%	41%	18%	8%	15%
SSA	247,352	9%	28%	23%	15%	24%	455,859	7%	24%	22%	15%	31%

Notes: access defined as hours of travel time to nearest town of 50,000 or more inhabitants.





Fig. 4. Sensitivity of estimates to changes in output prices. Note: PAC area estimates are based on profitability criterion (gross margins > \$250/ha) and disallow forest conversion, as shown in Table 3, columns 2 and 3.

nizing that productivity in African agriculture is very low also suggests that an opportunity for enhancing expansion potential may be offered by reducing yield gaps.

We evaluate the sensitivity of PAC estimates to variations in the attainable share of potential yields. Results are shown graphically in Fig. 5. Even modest improvements in productivity (or. equivalently, reductions in the yield gap) result in very large increases in estimated PAC. For example, an increase in attainable vield from 40% to 50% of the estimated potential yield (again assuming medium-input managers) results in an expansion of the PAC estimate by 68%; an increase from 40% to 80% results in an expansion of over 360%. While we agree strongly with Deininger and Byerlee's (2011) conclusions that agricultural productivity growth on existing cropland is the most favorable form of food production growth because it will reduce pressures to put additional land under production, at the same time it appears that land productivity growth will create economic incentives to bring additional land under cultivation (an idea sometimes referred to as the Jevons paradox; see Rudel et al., 2009 for a recent empirical exploration of this), unless the productivity response leads to a corresponding reduction in output prices and profitability.

Other constraints to expansion

There are certainly other constraints to land expansion in the region, particularly with respect to rainfed smallholder systems. This section examines some of these additional factors by comparing the location of PAC estimates with available information on *conflict and insecurity, endemic disease burden,* and *production uncertainty.*

As a measure of civil unrest and insecurity, we use the 2012 Ibrahim Index of African Governance (IIAG) to identify conflictprone countries as those with Safety & Rule of Law composite scores below 40.¹⁹ While admittedly coarse, this metric does capture what most observers would agree are the most conflict-prone areas in the region.

To address the prevalence of disease in tropical and sub-tropical environments, we determine the share of surplus land being located in the humid lowlands, which broadly defines exposure to the major diseases affecting human and animal productivity (e.g. malaria, tripanosomiasis). A useful proxy for this is a predicted distribution for malaria, which uses climate and elevation to spatially identify areas where malaria is endemic (Craig et al., 1999). The prediction is given in a fractile range of 0–1; we identify malaria-prone areas as those assigned .9 or higher. Disease burdens do not rule out land expansion, though the tsetse fly greatly constrains the use of mixed crop-livestock systems, and many farmers themselves cite malaria as a substantial constraint to migration.²⁰

Rainfed production is notoriously vulnerable to vagaries of weather, particularly of rainfall. Although the best way to conceptualize and measure such variability is a matter of continued debate (Faurès et al., 2010), here we simply use the coefficient of variation (CV) of seasonal rainfall to characterize relatively uncertain production environments. We define high variability areas as those places with a CV greater than the 75th percentile of grid cells currently being cultivated within the region.²¹

We use these three indicators to characterize the share of PAC that may face one or more of these constraints. Results are shown

¹⁹ These countries include: Chad, Côte d'Ivoire, Eritrea , DRC, CAR, Zimbabwe, and South Sudan, the last country not being included in the IIAG dataset.

²⁰ In another paper in this volume, Headey et al. conducted focus group questionnaires in 12 Ethiopian villages. Malaria prevalence was widely cited as a constraint to participation in the federal governments resettlement programme.

²¹ Of course, too much rainfall can also be a problem, particularly for pest control. However, we do not consider that particular constraint here.





Fig. 5. Sensitivity of estimates to attainable yield assumptions. Note: Criteria other than attainable share of potential yield are held constant, disallowing forest expansion, as in Table 3, columns 2 and 3.

in Table 5, using the suitability criterion and allowing forest conversion (the most generous estimate of PAC). In terms of conflict, we find that almost 50% of the surplus resources are located in conflict countries, in aggregate, although in East/Central Africa, where most potential cropland is located, the share within conflict countries is 80%. This reflects, in large part, the resources in DRC and South Sudan.

In terms of disease burdens, the vast majority of underutilized land resources are located in disease-prone areas. These results largely hold true for all the PAC estimates, although they are particularly large when forest conversion is allowed (since most forest resources in SSA are located in humid lowlands). This suggests that disease burdens could be an extremely important constraint on smallholder land expansion.

About 25% of the total PAC is located in areas with high rainfall variability, although most of this is in Southern Africa, where almost all the underutilized land is located in these high variability areas. Large shares of the surplus land stocks in places like Zambia and Angola are located in dry woodlands and savannah, where rainfall variability often implies precarious livelihoods from crop agriculture.

Together, these summaries provide some important reminders that our approach to measuring the viability of cropland expansion is still incomplete, and could indeed be improved upon in further research, especially if such research were able to quantify the costs of these other constraints. Although we do attempt to advance the economic assessment of land potential over previous efforts, we are still almost certainly under-representing the actual constraints involved in land expansion.

Finally, a major constraint to land expansion pertains to the high level of concentration of PAC in a few countries within the region. This concentration is largely invariant to alternative criteria or assumptions underlying the PAC estimate. Table 6 shows the countries comprising 80% of the total PAC resources within SSA under the various sets of assumptions we have looked at so far, ordered by contribution to total PAC. Although there are some differences, the degree of consistency in these alternative estimates is remarkable.

Another way to look at this is to examine whether or not the amount of PAC in land constrained countries is very sensitive to assumptions. We have already seen that the magnitude in aggregate is quite sensitive to assumptions about profitability and productivity, but this sensitivity largely plays out through the relatively few land-surplus countries. For land-constrained countries, varying such assumptions make little difference. To illustrate this, Fig. 6 shows how PAC varies as a function of the assumed attainable share of potential yield. For the most land abundant tercile of countries, there is a strong sensitivity (corresponding to the overall sensitivity shown in Fig. 5). For the most land-constrained tercile, the differences are negligible. This is true for all other assumptions as well. Upon reflection, this result is not surprising: the much acclaimed regional land abundance is simply not to be found in the countries which face the greatest needs for more farm land.

Conclusions and policy implications

Projections of higher and more volatile global food and energy prices into the foreseeable future have raised major concerns about how the world – and Africa in particular – is going to feed itself, and at what cost. There is widespread agreement that, to the extent feasible, achieving productivity growth on land already under cultivation is the preferred strategy because it would minimize the major environmental costs of greenhouse gas emissions and reduced biodiversity associated with the conversion of virgin land to agriculture (e.g., Hertel, 2011; Deininger and Byerlee, 2011). However, there are no assurances that the future rate of technical

Table 5

Share of PAC in areas prone to conflict, disease or high rainfall uncertainty.

Region	PAC (MHA)	(A) conflict countries	(B) disease prone areas	(C) areas of high rainfall variability	A B	A C	B C	A B C
East/Central	261	80%	93%	2%	96%	84%	95%	97%
Southern	141	5%	71%	76%	74%	84%	94%	94%
West	54	10%	99%	2%	99%	14%	99%	99%
SSA	456	49%	87%	25%	89%	76%	95%	97%

Note: PAC area estimates are based on suitability criterion and allow forest conversion, as shown in Table 3, column 4.

Table 6

Concentration of PAC under alternative assumptions.

	Without forest			Including forest			
	Suitable	Profitable		Suitable	Profitable		
	<i>n</i> = 9	Medium management n = 11	High management n = 12	<i>n</i> = 9	Medium management n = 10	High management n = 11	
Countries accounting for 80% of PAC	Sudan DRC Zambia Mozambique Angola Madagascar Tanzania Chad CAR Guinea Zambia	DRC Madagascar Sudan CAR Angola Mozambique Tanzania Zimbabwe Cameroon Zimbabwe Cameroon	DRC Sudan Angola Madagascar CAR Mozambique Zambia Tanzania Chad	DRC Sudan Zambia Mozambique Angola Tanzania Madagascar Cameroon Congo-Brazz. Tanzania Tanzania	DRC CAR Sudan Madagascar Angola Cameroon Congo-Brazz. Mozambique Gabon Gabon	DRC Angola Sudan CAR Madagascar Mozambique Cameroon Zambia Congo-Brazz.	

Note: countries are shown ranked in order of contribution to total PAC.



Fig. 6. Sensitivity of estimates to attainable yield assumptions, highlighting differences between land abundant and land scarce countries. *Note*: potential yields are based on medium-input management assumptions as described in text. Criteria other than attainable share of potential yield are held constant, disallowing forest expansion, as in Table 3, column 2.

innovation and productivity growth on existing cropland will be sufficient to avoid the need for some conversion of land to crop production, especially in Africa, where the rural population will continue to grow rapidly for the next 50 years, at least. Cultivated area expansion has been critical to the agricultural development of other land-abundant developing countries, even those experiencing reasonably impressive land productivity growth such as Brazil and Indonesia. In that regard, there may be important tradeoffs between environmental and social considerations.

The potential importance of cropland expansion to economic development in Africa has prompted several recent efforts to identify the magnitude and location of such potential. This study has demonstrated that the assertion that Africa is vastly land-abundant needs substantial qualification. Such assertions may in fact materialize, but only under a relatively narrow range of scenarios and future outcomes. In tenor, our analysis agrees with that of Lambin et al. (2013), who identify a number of factors potentially

inhibiting expansion. Methodologically, our analysis has focused on the economic constraints to expansion under a set of assumptions about costs and benefits. We show that estimates of potentially available cropland (PAC) are highly sensitive to assumptions about: (i) the minimum estimate of current population density below which land is considered to be "unutilized"; (ii) whether forest land is to be considered available for conversion to agriculture, given the potentially massive associated costs to the environment and to biodiversity; (iii) the minimum net returns to land below which cropland expansion is not considered economically viable; (iv) spatially-varying prices, and (v) assumptions about the extent to which the gap between potential and actual yields will be narrowed. In contrast to the oft-quoted estimate of roughly 200 million hectares of unutilized suitable cropland in Sub-Saharan Africa, it may be more appropriate to think of the potential for cropland expansion in terms of a distribution that is highly sensitive to assumptions and future outcomes. Some of our estimates of potentially available cropland are as high as 400 million hectares. However, the assumptions that generate these estimates are: (1) that infrastructure gaps will be closed relatively quickly; (2) that destruction of forests and other ecological assets is costless; and (3) there are no other important costs or constraints on land expansion (institutions, conflict, disease and so on). In the short to medium term - that is, without major infrastructural investments - our estimates of 80-167 million hectares (columns 2 and 3 of Table 3) represent a relatively small area, especially given Africa's present rates of population growth. Moreover, roughly 20 million hectares have already been transferred to largescale foreign investors in Sub-Saharan Africa (see Schoneveld, 2014), further limiting the potential for smallholder land expansion in the medium term. Conceivably, large commercial farms could more profitability exploit more land than smallholders if scale economies could be achieved. This paper has not explicitly addressed the scale-dependent profitability of land expansion in Africa due to limited data on production costs, although our examination of the sensitivity of our main results to different

Table A1
Comparison of estimates of cultivated and forested areas (1000s of hectares)

Country	Rural	Cultivated area			Forested area		
	Land area	GAEZ	GlobCover	MODIS	GAEZ	GlobCover	MODIS
Angola	125,000	3566	3921	3562	58,700	73,200	22,900
Burkina Faso	26,100	4671	11,400	13,900	2110	1489	1
Cameroon	45,000	6786	3774	5165	23,400	30,600	23,000
CAR	61,600	1977	1403	814	23,700	43,100	8790
Chad	123,000	8242	9539	13,400	2450	11,800	29
DRC	226,000	15,300	12,200	13,000	147,000	179,000	139,000
Congo-Brazz.	33,900	617	1237	4972	23,300	23,000	23,000
Ethiopia	111,000	14,500	18,800	24,900	8388	24,600	4643
Gabon	25,600	462	800	1210	21,200	21,600	23,300
Kenya	55,900	4841	7275	8170	4199	10,500	1238
Madagascar	57,800	3697	2527	3489	12,700	15,700	10,100
Mali	113,000	8487	15,000	17,200	3426	3310	5
Mozambique	75,900	6131	6040	1837	24,500	47,200	8032
South Africa	108,000	12,400	8578	8549	7570	17,100	2258
Sudan	246,000	16,400	17,600	31,900	10,400	34,900	502
Tanzania	87,700	11,900	9745	10,600	24,300	39,400	4542
Zambia	72,900	5071	2060	1635	30,800	44,800	9420
East/Central	970,008	82,885	84,116	122,304	248,196	372,134	183,406
Southern	628,368	39,874	32,162	21,434	154,616	217,826	53,768
West	541,592	87,756	83,800	143,189	99,681	118,985	73,850
SSA	2,139,968	210,516	200,079	286,927	502,492	708,944	311,024

Notes: GAEZ land cover is a synthesis of several datasets, as described in the text. GlobCover is GlobCover 2009. Modis is the collection 5 for 2010, using the International Geosphere–Biosphere Programme (IGBP) classification.

Table A2

Comparison of actual and potential yields for maize in Zambia.

Yields	Management level	Mean	p10	p25	p50	p75	p90
Potential	Low/subsistence	2.6	1.2	2.2	2.6	3.3	3.6
	Medium	5.3	2.5	3.6	5.9	7.1	7.4
	High/commercial	7.2	3.3	4.9	8.0	9.5	10.3
Actual	Medium	2.3	0.6	1.0	1.8	3.1	4.4
Actual/potential	Medium	43%	23%	29%	31%	43%	60%

Notes: Potential yields are the "agroclimatically attainable yields" given in GAEZ 3.0 for rainfed production under the 3 defined management levels, for maize producing areas in Zambia. Actual yields are observed for smallholder farmers, from the Rural Agricultural Livelihoods Survey for 2012. Smallholders in the survey use a range of input levels, but few are exclusively subsistence or exclusively commercially oriented; here we consider this group as primarily medium-level managers, as defined in the GAEZ 3.0 documentation. Distributions shown are for all of Zambia; however, calculating ratios between actual and potential yields at local levels gives similar results.

profitability thresholds (Fig. 2) and attainable yields (Fig. 5) do suggest that scale economies in commercial farming may enable expansion in some areas. A controversial paper by Collier and Dercon (forthcoming) makes arguments broadly along these lines, and suggests the need for African governments to learn more from the experience of large-scale farming in Brazil and other successful transforming economies. This is certainly an area for future research.

Over the longer run, the potential for profitable cropland expansion could rise substantially as market access conditions in the hinterland improve. As urban centers in the interior expand (as we have every reason to believe they will), local demand for agricultural output will increase, providing incentives for marketoriented production in areas which may currently be considered inaccessible. The improvement of infrastructure that tends to accompany the growth of towns should further enable this. Additionally, of course, the potential for profitable smallholder expansion could rise substantially on the back of targeted road and/or irrigation investments.²² But such changes are not a foregone conclusion: Sub-Saharan Africa currently faces major infrastructural problems even in its relatively densely populated areas and the region as a whole has less than one-quarter of the paved road density of other low-income countries (Foster, 2008). The African Infrastructure Country Diagnostic (AICD) reports that the cost of providing infrastructure in areas of less than 15 people per square kilometer is double the cost of providing infrastructure in cities (Foster, 2008). Much of the requisite infrastructure is also required in fragile states prone to conflict and poor governance (particularly the DRC and South Sudan). It would therefore appear that road construction in many of the remote parts of Africa may proceed relatively slowly.²³

Another critically important constraint is that almost all of the available land for crop expansion is located in a small handful of countries. Outside of these countries, the availability of underutilized land resources appears to be relatively limited. In a borderless Africa, farmers in land-constrained areas could move to these land-abundant countries and regions to circumvent existing land constraints. In reality, African households face major risks and transaction costs in moving across borders or even to other parts of the same country controlled by different ethnic groups. In the past, such migration has often contributed to violent and tragic ethnic conflict, as observed in wars in the eastern DRC and Cote d'Ivoire, to name just two examples.

 $^{^{\}rm 22}\,$ See You et al. (2011) for an assessment of the untapped irrigation potential in the region.

²³ This stylized story notwithstanding, concentrated investments have the potential to "open up" frontier areas relatively quickly. See Weng et al. (2013) for recent evidence of relatively rapid development of infrastructure corridors in Africa, driven largely by expansion of mining activities in hitherto remote areas; they argue that such investments will be important drivers of land use changes in the near future.

It should be emphasized that our analysis is almost certainly under-representing the true costs of land expansion in the short to medium term. A significant share of underutilized land in Africa is characterized by relatively high levels of rainfall uncertainty, even within "suitable" production areas. Combined with isolation from markets and public services, many "under-used" areas with unreliable rainfall would pose serious risks to smallholder land expansion, and substantial profit risks to input-intensive commercial farming. The costs associated with cultivation in areas of high social conflict and/or with heavy disease burdens are surely considerable, but are not captured within our profitability framework. Such costs may well underlie the low levels of activity observed in many otherwise attractive areas.

Finally, it remains unclear as to whether areas with low population density are truly underutilized. Of particular concern is the fact that many low density areas are already used for pastoralist livestock production and/or wildlife migration corridors, while many forested areas are inhabited by indigenous peoples who rely on the existing biosystem and would be adversely affected by changes to it. Both of these extensive production systems arguably make efficient and sustainable use of natural resources, and it is far from obvious that cropland expansion is the appropriate (or just) use of these resources, even where such expansion might be profitable from a farm perspective.

A. Appendix

See Tables A1 and A2.

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