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Can healthy diets be achieved worldwide in 2050 without farmland expansion?

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Abstract

This paper analyses to what extent it would be possible to ensure food availability to the world population by 2050 with two objectives: healthy diets and no farmland expansion. Assumptions were made to project exogenous demand and supply variables. Climate change impacts on crop yields, grazing use intensities and maximum cultivable areas were taken into account. Cropland and pastureland needs were then estimated for 21 regions using a global biomass balance model. Simulation results established for two sets of crop yield projections ('moderate' *versus* 'high' growth) show that several regions (India, Rest of Asia, Near- and Middle-East countries and North Africa, as well as West Africa in the case of 'moderate' yield growth) would be constrained by their maximum cultivable areas with no deforestation. Our scenarios would be technically infeasible because of additional pastureland needs notably in sub-Saharan Africa. As a consequence, we analyse to what extent additional levers could reduce pastureland needs in sub-Saharan Africa.

Graphical abstract

See separate file

Keywords: Climate change; Cropland; Pastureland; Deforestation; Yields; Global food availability.

1. Introduction

A growing number of studies aim at addressing world food security. Based on a textual analysis of 12,640 research articles published between 1969 and 2018, Tamburino *et al.* (2020) concluded that a large majority of studies were centered on agricultural production aspects with only 3.4% of works published over the more recent period 1995-2018 including demand side aspects. Furthermore, although the key words ‘crop yields’ and ‘land use’ appeared frequently, ‘pasture’ and ‘pastureland’ were almost absent. In this paper, we considered both supply and demand side aspects of regional food availability pointing out impacts on farmland use projections in 2050, with particular attention on pastureland needs.

The 2012 revision of the FAO report on ‘World Agriculture towards 2030/2050’ (Alexandratos and Bruinsma, 2012) is likely the most publicised world food projection exercise. In line with similar studies developed at that date that relied on a business as usual (BAU) scenario (e.g., McIntyre *et al.*, 2009; Tilman *et al.*, 2011), Alexandratos and Bruinsma (2012) concluded that world agricultural production should increase by 60% from 2005-2007 to 2050 to meet demand by this horizon. This figure derived from a single scenario has been discussed based on methodological, environmental or political considerations. Critics were partially taken into account in the 2018 FAO report on ‘The Future and Food and Agriculture’ (FAO, 2018), as well as in several modelling exercises developed after 2012 (e.g., Mora *et al.*, 2020; van Meijl *et al.*, 2020), by including complementary scenarios based on alternative assumptions for key change drivers.

This paper adopts a normative assumption of regionalised healthy diets worldwide in 2050 based on nutritional recommendations (The EAT-Lancet Commission on Food, Planet, Health, 2019; Clark *et al.*, 2020; Mora *et al.*, 2020). It adopts a second normative objective by excluding any farmland expansion that could lead to deforestation since the latter is a key factor of greenhouse gas (GHG) emissions (Baker and Spracklen, 2019) and biodiversity loss (Xiam, 2017). A zero deforestation assumption was also adopted by Erb *et al.* (2016) who explored the biophysical option space for feeding the world in 2050. Our analysis differs from that of Erb *et al.* (2016) insofar as in our study diets were supposed to be healthy in 2050, and cropland and grassland needs were endogenously determined. Furthermore, land imbalances were assessed at regional level. Bouwman *et al.* (2010) and Pardey *et al.* (2014) also assumed no change in forest area, but their analyses were limited to bioenergy production and cropland expansion, respectively. More recently, Bahar *et al.* (2020) developed a meta-analysis aimed at assessing the impacts on forest areas by 2050 or 2100 of 63 scenarios. They found that 11 scenarios predicted no change in forest area by 2050, and 20 scenarios allowed forest area to expand by 2050 up to a maximum of 2.8 billion hectares. In these 31 scenarios, forest stability or gain did not jeopardize future food production because the scenarios also assumed high increases in crop yields (most often in the implicit form of yield gap reductions), substantial dietary changes (notably with lower consumption of animal products), and decreases in food waste and losses. Our paper differs from these studies by assessing whether agricultural land productivity evolutions impacted by CC would allow the achievement of healthy diets by 2050 without farmland expansion.

Our analysis was developed at the level of 21 world regions (**SM1**) and 33 agri-food products (**SM2**). We first focused on the role of crop yields that would evolve under the combined influence of technological developments and CC (Aggarwal *et al.*, 2019). By contrast with, for example, Erb *et al.* (2016), van Ittersum *et al.* (2016) or Clark *et al.* (2020), we did not pose arbitrary assumptions regarding possible reductions in yield gaps by 2050. Instead, we explicitly relied on crop yield projections that allowed us to define two sets of yield projections corresponding to an optimistic *versus* more pessimistic pattern of technological developments. In both cases, yield projections were impacted by CC based on results of the meta-analysis of Makowski *et al.* (2020). We also took into account how technological developments and CC could impact productivity in the livestock sector. Contrary to a large majority of works that considered only cropland needs (e.g., van Ittersum *et al*., 2016; Wenbin *et al*., 2018), pastureland requirements will also be provided.

According to our modelling assumptions and simulation results, achieving healthy diets in 2050 without further farmland expansion – implying no deforestation - would not be possible in several parts of the world, in particular in sub-Saharan Africa (SSA) because of agricultural land needs, more specifically of pastureland needs. To achieve the desired outcome, some assumptions that underlie our baseline simulations must be revised. The plausibility of these alternative/complementary assumptions is discussed.

2. Modelling framework and assumptions

The modelling framework is summarized in **Figure 1** that distinguishes entry parameters and exogenous variables of the model from endogenous variables whose levels are simulated in 2050. The model is a global biomass balance model (Mora *et al.*, 2020) adjusted for the exercise as regards livestock equation parameters and in particular feed efficiency parameters (**SM10**). In each region and for each product, supply (domestic production + imports) is equal to demand (domestic uses + exports + waste + stock variation) for both the reference period "2010" (average 2009-2010-2011, hereafter "2010") and the simulation horizon 2050. Global consistency is achieved when world exports of each traded product are equal to world imports (see below).

Figure 1

Food consumption regional levels evolved from base period levels towards healthy diets in 2050 that correspond to a daily calorie intake of 2,750-3,000 kcal per person (depending on the region) and a regional product composition in accordance with nutritional recommendations (**SM3**). The uncertainty space related to domestic demand variables in each region was reduced by i) adopting a single demographic projection based on the median of the 2022 revision of world population prospects (United Nations, 2022), ii) establishing a single projection for agricultural feedstock used for biofuel production (**SM4**), and iii) assuming the constancy in percentage of food waste and losses at the various stages of the food chain. Feed uses of plant products were endogenously determined based on fixed technical coefficients (see below).

On the supply side, crop yields evolved under the influence of technological developments in interaction with CC by 2050. The impacts on yields of CC parameters, that is, temperature, rainfall and atmospheric concentration in carbon dioxide (CO_2), were evaluated based on a statistical relationship derived from a meta-analysis distinguishing C3 and C4 plants (Makowski *et al.*, 2020). Technological developments encompassed increases in input uses, increased efficiency of inputs notably for seeds thanks to genetic progress, and increased efficiency in input use. Changes in yields induced by technological developments were defined in the form of an interval. The upper bound corresponds to the rather optimistic assumption adopted by the FAO in 2012 with corrections for a few crops in a few regions based on historical data and expert judgement that are detailed in SM5 while the lower bound reproduces the comparatively more conservative assumption of the BAU scenario in the 2018 FAO report. This led us to define two data sets for crop yields in 2050 (**SM5**). The first set of ‘moderate’ yield increases included moderate technological developments preventing any ability for plants to exploit the rise in atmospheric CO_2 concentration. The second set of 'high' yield increases assumed more optimistic technological developments, including in terms of water and fertiliser access, permitting the full field expression of the CO_2 effect (Toreti *et al.*, 2020). In both sets, CC regional variables were supposed to follow climatic projections of the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 6.0 (Allen *et al.*, 2019). It is worthwhile to note that the time horizon of 2050 is too close to significantly differentiate yield impacts of temperature and rainfall projections of the RCP 6.0 from those of more pessimistic climate futures. Cropping intensities were maintained constant at base period levels (**SM6**) given the great uncertainty that surrounds this variable and its evolution (IIzumi and Ramankutty, 2015). For the same reason (Erb *et al.*, 2016; Fetzel *et al.*, 2017; Squires *et al.*, 2018), permanent grassland yields, approximated here by grazing intensity estimates, were supposed to evolve only under the influence of CC without technological developments (**SM7**). This assumption will be relaxed in sensitivity analyses.

We paid particular attention to the modelling and calibration of feed efficiencies because the latter are an essential determinant of cropland and pastureland needs. In each region, we distinguished seven categories of animal products, that is: pork, poultry, eggs, milk from all ruminants, bovine meat, meat of small ruminants, and aquaculture production. Each of these seven sectors was modelled as a Leontief production function (fixed transformation coefficients) with respect to feedstuffs (cereals, oilseeds, other concentrate feedstuffs, permanent grass, temporary grass, other cultivated forages, occasionals and crop residues). In the case of monogastrics (pork, poultry and eggs), feed efficiencies in "2010" were calculated on the basis of national statistics of the compound feed industry adjusted according to expert advice to ensure their consistency between species and regions. In the case of large ruminants, feed efficiencies were estimated by developing a specific demographic model and relying on the IPCC Tier 2 methodology and different complementary data sources. For meat from small ruminants and aquaculture products, feed efficiencies were derived from Bouwman et al. (2005) and Herrero et al. (2013). **SM8** details how feed efficiencies were calculated for "2010" and projected to 2050.

Maximum cultivable areas by 2050 impacted by CC were defined from the fourth version of the land classification of Global Agro-Ecological Zones (GAEZ) developed by IIASA (International Institute for Applied Systems Analysis) and FAO (Fischer *et al.*, 2021). In our study, land areas with a GAEZ sustainability index greater than 40 in 2050 were supposed to be cultivable (**SM9**). We also excluded cultivable areas occupied by forests in accordance with our no deforestation assumption preventing any cropland expansion on forest areas. Cropland expansion can therefore only take place at the expense of pastures and other land uses such as non-grazed shrubs or sparsely vegetated areas provided the latter are cultivable.

Trade was modelled by distinguishing imports and exports. Regional imports of each traded product were modelled as a share of total regional uses of that product and regional exports of each traded product were modelled as a share of world exports of that product. Initial import and export shares were calibrated based on "2010" data. These shares were maintained constant in 2050 in simulations and regions where the land constraint on maximal cultivable areas was not binding at that horizon. In that case, regional imports and exports of each traded product between "2010" and 2050 varied proportionally with total regional uses and world exports, respectively. When a region was land constrained in 2050, regional exports were reduced by decreasing equi-proportionally the "2010" export coefficients for all traded products in the constrained regions. If the decline in exports was not sufficient to make the regional land constraint no longer binding, imports were increased by increasing equi-proportionally the "2010" import coefficients for all traded products in the regions that were still land constrained after the reduction of their exports. In that second case, export shares and possibly import coefficients become endogenous parameters. This trade modelling framework thus relies on an implicit assumption of an unchanged structure of international trade except in regions with binding land constraints in 2050. This somewhat rigid assumption was relaxed in the sensitivity analysis for SSA in the results section.

Within this set of assumptions for demand, supply and trade components, we evaluated regional cropland and grassland areas by 2050 that would be required to meet the normative targets of healthy diets and no farmland expansion.

3. Results

3.1. Cropland needs in 2050

If all other supply and demand parameters and variables were maintained unchanged at "2010" levels, world population growth would increase global cropland needs by +562 million ha in 2050 (+37 % with respect to "2010") that would be geographically very unevenly distributed with the two SSA regions concentrating half of additional needs, that is, +151 million ha (+113 %) in East, Central and South (ECS) Africa and +128 million ha (+131 %) in West Africa (**Table 1**). The normative assumption of healthy diets by 2050 would induce supplementary cropland needs of +303 million ha (+20%), again essentially in ECS and West Africa (+101 and +75 million ha, respectively) as well as in India (+82 million ha). The effect of the plant component of healthy diets on cropland needs would be positive in all regions. At the world level, this effect (+256 million ha) would be more than five times higher than the effect of the animal component of healthy diets (+47 million ha). The latter would be negative in many regions but not in all. It would be positive in the four regions where healthy diets would lead to increases in the per capita consumption of animal products, that is, West Africa (+64 million ha), ECS Africa (+29 million ha), India (+19 million ha) and Rest of Asia (+2 million ha). It would be very slightly positive in North Africa (+1 million ha) and null in Rest of America. It would be negative in all other world regions, up to a maximum of -33 million ha in Canada-USA. Worldwide additional cropland needs induced by projections to 2050 of biofuel uses and other non-food uses would be limited to +27 million ha (+2 %).

The combined effects of all demand drivers would increase world cropland needs by +892 million ha (+58 %) including +253 million ha in ECS Africa (+188 %), +205 million ha in West Africa (+209 %), +135 million ha in India (+80 %) and +84 million ha in Rest of Asia (+49 %). Additional cropland needs in the nine other regions (with all European regions combined into a single aggregate region) would be limited to +215 million ha in total, from +35 million ha in Brazil-Argentina to -2 million ha in China. However, changes expressed in percentage reveal critical regions where “2010” cropland areas were low. This is the case for North Africa and Near- and Middle-East (NME) countries where cropland needs would rise by +92 % and +60 %, respectively. Tensions in these two regions would be exacerbated by the fact that possibilities to expand agricultural areas would be very limited (see below).

Table 1

On the supply side, changes in animal feed efficiencies would induce only very small effects on cropland needs for a world total of +7 million ha (**Table 2**). This outcome may appear counterintuitive. It can be explained by the fact that evolutions of animal feed efficiencies capture different effects that act in opposite ways. On one side, technological improvements reduced cropland needs required to feed livestock. On the other side, cropland needs were increased by changes in animal ration compositions linked, first to the reduction of backyard monogastric farms (that implies a decrease in ‘occasional’ feed items that do not need agricultural areas and their replacement by ‘crop’ feed items), second to the increased quality of dairy cow rations needed to produce more milk per animal that requires higher quality forages. By contrast, increases in crop yields would allow alleviating world cropland needs in 2050 by -617 million ha (-40 %) in the case of ‘moderate’ yield growth (Table 2, panel a) and by -872 million ha (-57%) in the case of ‘high’ yield growth (Table 2, panel b). In the ‘moderate’ hypothesis, a rather conservative pattern of technological developments would decrease global cropland needs by -701 million ha (-46%) but temperature and precipitation changes would increase these needs by +84 million ha (+5 %). In the ‘high’ hypothesis, more optimistic technological developments evolutions would diminish cropland needs by -830 million ha (-54 %) and the field expression of the CO_2 fertilisation effect would make CC impacts reduce these needs by -42 million ha (-3 %).

Demand and supply effects combine to define cropland need changes by 2050. At the world level, the latter would be equal to +282 million ha (+18 %) for ‘moderate’ crop yield evolutions and to +27 million ha (+2 %) for ‘high’ crop yield evolutions. Consideration of the land constraint linked to both maximum available cultivable areas and the assumption of no deforestation did not significantly alter world additional cropland needs in 2050 (+251 *versus* +282 million ha for ‘moderate’ crop yield changes and +25 *versus* +27 million ha for ‘high’ crop yield changes). However, these global figures mask more important regional changes with cropland area decreases in regions where the land constraint would be binding compensated by increases in regions where there would be cultivable land availabilities.

In total, cropland need changes would be high in the two SSA regions even in the case of ‘high’ crop yield increases (+70 and +55 million ha in ECS and West Africa, respectively), let alone in the case of ‘moderate’ crop yield increases (+145 and +83 million ha in ECS and West Africa, respectively). Cropland area needs would be largely inferior to 2050 maximal cultivable areas in ECS Africa whatever the crop yield evolution, ‘moderate’ or ‘high’. The land constraint in 2050 would also not be binding in West Africa in the case of ‘high’ crop yield increases but would be binding in the case of ‘moderate’ crop yield increases. In that case, the binding land constraint would induce a decrease in 2050 cropland areas in West Africa compared to regional needs with no land constraint (from 118 to 83 million ha) and an increase in net imports of that region (by +38% in calorie equivalent).

Four other regions would be land constrained when crop yields evolve ‘moderately’ and forced to decrease their cropland areas in 2050 by -30 million ha in India, -29 million ha in North Africa, -15 million ha in NME countries and -8 million ha in Rest of Asia (differences with respect to cropland areas in 2050 with no land constraint). These four regions would be also land constrained in the case of ‘high’ yield increases with however lower decreases in cropland areas (-6 million ha in India, -20 million ha in North Africa, -6 million ha in NME countries and -8 million ha in Rest of Asia). This contrasts with cropland needs in Europe, Canada-USA, Brazil-Argentina, Rest of America, FSU, China and Oceania where cropland areas in 2050 would remain much lower than their respective maximal cultivable areas with no deforestation. In the case of ‘high’ crop yield growth, 2050 cropland areas in Europe, Canada-USA, FSU and China and Europe would be even lower than "2010" cropland areas (this would also be the case for FSU and China with a 'moderate' yield growth). These "reservoirs" of cultivable areas that were cultivated in "2010" and would no longer be cultivated in 2050 offer the theoretical physical possibility of their exploitation – provided they are not mobilised to satisfy changes in pastureland needs – for alleviating, thanks to further increased exports, the land constraint in other regions.

Table 2

3.2. Permanent pastureland needs in 2050

In the case of 'moderate' yield growth, theoretical world permanent pastureland (hereafter named more briefly pastureland) needs would increase by +2.31 billion ha (+72 %), from 3.20 billion ha in "2010" to 5.51 billion ha in 2050 (**Table 3, panel a**). Pastureland needs in 2050 would be extremely high in SSA, with increases of +379 % in West Africa (from 145 to 695 million ha) and +281 % in ECS Africa (from 551 to 2,100 million ha) under the combined effect of very dynamic population growth and the evolution towards healthy diets that implies, in these regions, increases in the per capita consumption of red meat and dairy products (see SM3). Large increases in pastureland needs in 2050 can also be attributable to conservative projections of supply variables related to grazing intensities and feed efficiencies (see SM7 and SM8). The picture is barely more pessimistic in the second case of 'high' growth of crop yields (**Table 3, panel b**) that however would reduce the need of world pastureland expansion by 2050 to +2.07 billion ha (-238 million ha with respect to the case of 'moderate' crop yield evolutions), including +638 million ha in West Africa (+88million ha) and +1,409 million ha in ECS Africa (-140 million ha). The fact that pastureland needs in West Africa would be greater in the case of 'high' crop yields than in the case of 'moderate' crop yields may be puzzling. This outcome is explained by the fact that this region is constrained in 2050 by its cultivable area when crop yields are ‘moderate’ but is not when crop yields are ‘high’. In this second case, West Africa would therefore increase further its domestic agricultural production, including that of animal products, instead of increasing its net imports of agricultural products.

In total, the no farmland expansion objective appears technically impossible in several other regions in the first place in ECS Africa and West Africa but also in Rest of America, India, Rest of Asia, North Africa, NME countries and Oceania (as well as in Europe and Brazil-Argentina in the case of ‘moderate’ crop yield changes). In all these regions, increasing pastureland areas by 2050 would require farmland expansion. In the two SSA regions, farmland needs would even largely exceed regional emerged areas making our scenarios not only technically impossible but physically infeasible.

Table 3

3.3. Options for reducing pastureland needs in SSA

Table 4, panel a for West Africa and panel b for ECS Africa, analyses to what extent it would be possible to make the scenario of healthy diets and no farmland expansion technically feasible in SSA based on alternative assumptions for some supply and demand variables in 2050. This was done for the less unfavourable baseline scenario in terms of total agricultural land needs corresponding to a ‘high’ growth of crop yields. We started by assuming that grazing intensities would increase in all world regions by +30% in 2050 with respect to “2010”. This first variant would make the no farmland expansion objective possible or almost possible in all world regions (**SM12**) except in SSA despite substantial decreases in 2050 pastureland needs (from 783 to 620 million ha in West Africa and from 1,960 to 1,551 million ha in ECS Africa). The second variant assumed in addition that ruminant feed efficiencies would be +20% higher in 2050 in the two SSA regions than baseline scenario levels at that date. This would allow an additional sparing of pastureland of +106 million ha in West Africa and +230 million ha in ECS Africa. The third variant further assumed the substitution of red meat by white meat in 2050 healthy diets in the two SSA regions. Specifically, we assumed that the per capita meat consumption levels in 2050 in the baseline scenario were unchanged (24 kg/habitant/year in West Africa and 28 kg/habitant/year in ECS Africa) but with less red meat (from 14 to 6 kg/habitant/year in West Africa and from 16 to 10 kg/habitant/year in ECS Africa) replaced by white meat (from 10 to 18 kg/habitant/year in West Africa and from 12 to 18 kg/habitant/year in ECS Africa). This third variant would reduce pastureland needs in 2050 by -65% in West Africa (from 783 to 273 million ha) and by -50% in ECS Africa (from 1,960 to 981 million ha). Finally, the fourth variant in which import shares of ruminant products were increased to 0.35 in 2050 in SSA would allow an additional reduction of pastureland needs of -57 million ha in West Africa and of -298 million in ECS Africa. Cropland needs would also be impacted by the four levers but only marginally.

To sum up, the four modelled drivers would significantly reduce pastureland needs in 2050 in the two SSA regions. However, the reductions would not be sufficient to make a no farmland expansion objective technically possible. More disruptive supplementary levers must be envisaged.

Table 4

4. Discussion

From the joint perspective of food availability and environment protection, agricultural land use management must not be restricted to cropland needs as in, for example, Tilman *et al.* (2011), van Ittersum *et al.* (2016) or Pastor *et al.* (2019). Attention must be extended to pastureland needs.

4.1. Cropland needs

According to our simulation results, achieving healthy diets in 2050 would lead several world regions to be constrained by their cultivable land availabilities with induced increases in food net imports (**SM11**). This would be the case in India, Rest of Asia, NME countries and North Africa, as well as West Africa in the case of 'moderate' yield growth. These cropland needs are globally consistent with those of the literature summarized in Le Mouël and Forslund (2017) who reported world cropland expansion ranking from +0 to +182 million ha in 2050 with respect to 2010 levels on the basis of a review of 25 studies, with discrepancies depending on scenarios and models. This review pointed out the same regions where cropland expansion would be the most important. The fact that additional cropland needs in the case of 'moderate' evolutions of crop yields would be more important in our study (+251 million ha) than the upper bound of the interval defined by Le Mouël and Forslund (2017) may be explained by two main factors. First, we imposed that diets would be healthy in all world regions implying an increase in the per capita calorie intake as well as in the individual consumption on animal products in several regions of the planet (notably in SSA). Second, we adopted rather conservative assumptions to project some parameters and variables by 2050, notably cropping intensities, feed efficiencies, and food waste and losses.

Increasing cropping intensities (that were supposed unchanged at base period levels in our study) is clearly a powerful solution for boosting crop production without yield increases and cropland expansion (Wenbin *et al.*, 2018). However, this driver raises questions related to the environmental impact of multiple-cropping systems in relation with green and blue water availability and appropriation (Waha *et al.*, 2020). From a modelling point of view, cropping intensity increases that were adopted in studies that actioned this lever were essentially postulated. This is especially the case in studies that reasoned in terms of cropping intensity gap reduction (Ray and Foley, 2013). Furthermore, Yu *et al.* (2021) raised the question of a focus on cropping intensities only while ignoring other measurements, specifically crop duration. In the same way, expanding further irrigated areas will increase the pressure on global freshwater resources leading possibly to their unsustainable use (Jägermeyr *et al.*, 2017).

Large uncertainty surrounds estimates of food waste and losses (Xue *et al.*, 2017). The latter could not be reduced without significant behavioural changes and strong public policies (Spang *et al.*, 2019). In that perspective, despite local successful initiatives and a growing awareness by the different actors of the food chain, there is no evidence that amounts of food waste and losses have decreased worldwide over the recent period. Worse still, Hegnsholt *et al.* (2018) estimated that they should increase from 1.6 billion tonnes today to 2.1 billion tonnes by 2030. Furthermore, very strong food needs in regions such as SSA would increase the volumes of agricultural goods to be managed. Under such conditions, reductions in rates of food waste and losses should be very important to induce substantial decreases in absolute amounts of wasted quantities, requiring significant investment in collection, storage, transport and distribution infrastructures.

4.2. Permanent pastureland needs

Our simulation results suggest that pastureland needs would be extremely high in 2050, notably in SSA where our baseline scenario would be technically infeasible even with complete deforestation; farmland needs would even exceed emerged areas. Simulated pastureland needs would be much higher than those of a large majority of studies that reported these needs in either BAU-type scenarios or more disruptive scenarios (Le Mouël and Forslund, 2017; Bahar *et al.*, 2020). In the following of this sub-section, pastureland need estimates in 2050 are discussed in the light of assumptions adopted for diets, grazing intensities and animal feed efficiencies. Uncertainties surrounding base period pastureland areas are also commented. Attention is focused on SSA.

Very high pastureland needs in SSA by 2050 (more than +300 % with respect to “2010”) partly result from the normative assumption of healthy diets that implies in that part of the world increases in the per capita consumption of red meat and dairy products associated with an important regional population growth. By comparison, Bajželj *et al.* (2014) estimated that pastureland areas in SSA would expand by +65 % in a BAU scenario, by +38 % when agricultural and food waste was further reduced by half, and by +12 % when diets were also supposed to be healthy. However, evolutions towards healthy diets correspond to two contrasted patterns for individual red meat consumption in SSA that would decrease by -17 kcal/habitant/day in Bajželj *et al.* (2014) but would increase by +35 kcal/habitant/day in our study, as well as for dairy products whose consumption would increase significantly less in Bajželj *et al.* (2014) than in our study. This specific comparison raises the question of the composition of healthy diets, more specifically of respective magnitudes of the different animal products in the latter. Healthy diets in our study were defined on the basis of the “healthy” scenario of the Agrimonde-Terra foresight exercise (Mora *et al.*, 2020). However, plant-forward diets that adhere to nutritional recommendations for healthy diets can be much more diverse with notably varying levels of animal products (Bajželj *et al.*, 2014; Erb *et al.*, 2016; The EAT-Lancet Commission on Food, Planet, Health, 2019).

In our study, changes in diets are perhaps more realistic because they took account of regional specificities of current diets.

Our modelling assumptions for pasture grazing intensities by 2050 are conservative since they were supposed to be influenced by CC only without any technological development. In each of the 21 regions, this assumption translates into pasture grazing intensity changes that are slightly negative in the baseline scenario of 'moderate' yield growth and slightly positive in the case of 'high' yield growth. In SSA, this stacks with low initial pasture grazing intensities (0.53 and 0.63 tonnes of dry matter per ha in West and ECS Africa, respectively). These two factors – no technological developments and low initial pasture grazing intensities – contribute to explain the important increases in pastureland areas required to achieve healthy diets in SSA.

Assumptions adopted for pasture grazing intensity evolutions deserve consideration notably because rainfall induced by CC should increase in some world regions. This is expected to have a positive impact on pastureland productivity but at the possible expense of increased inter-annual variability (Katzenberger *et al.*, 2021). In that perspective, Erb *et al.* (2016) assumed, but without justifying it, that estimated grazing intensities by 2050 would be far above their 2000 base period levels. Notwithstanding this assumption, they concluded that around one quarter of the 500 zero-deforestation scenarios they simulated would be limited by grazing constraints. This issue was addressed by the first variant of our baseline scenario. This variant suggests that increasing SSA pasture grazing intensities by +30 % in 2050 with respect to "2010" would allow a significant decrease in pastureland needs that however would remain largely too high for making a no farmland expansion scenario technically feasible in that part of the world (Table 4).

Following Herrero *et al.* (2013), Schiavo *et al.* (2021) considered that each of the three ruminant livestock sectors (milk and dairy, beef meat, small ruminants) was made up of four production systems (mixed, pastoral, urban and other systems). Feed efficiency, measured by the feed-to-output ratio, was supposed to improve significantly by 2050 in both the mixed and pastoral systems by extending projections established by Bouwman *et al.* (2005) through 2030. Furthermore, for the beef meat sector in West and ECS Africa, Schiavo *et al.* (2021) assumed that feed-to-output ratios decreased twice as fast, thereby reducing pastureland needs in these two regions (other things being equal). In practice, numerous studies relied more or less explicitly on the work of Bouwman *et al.* (2005) who assumed that the pre-2020 trend in grassland areas (+4 % only over the three decades 1970-2000 at the world level) would implicitly continue in the future, implying a rapid intensification of grassland management (in order to increase pasture grazing intensities) and decreases in forage-to-output ratios (in order to reduce forage needs per unit of ruminant product). These strong assumptions may be challenged since about 70 % of small and large ruminants are dependent on grazing natural pasture as the main component of their feed diet (Herrero *et al.*, 2015). As for pasture grazing intensities, feed-to-output ratios are very difficult to estimate (Alexander *et al.*, 2016). The choice adopted in this study was that of their spatial and temporal consistency on the basis of a specific modelling work described in SM8. This is at the cost of simplifications, notably by considering a single archetypal production system for each livestock sector. The second variant of our baseline scenario suggests that improving ruminant feed efficiencies in SSA would substantially reduce their pastureland needs (Table 4). This would require that meat and milk production functions become everywhere as important as other services provided by cattle (organic fertilization, draught animal power, income stabilizer) with improved livestock management systems.

In the same way, great uncertainties surround base year estimates of permanent pasture areas. According to the FAOStat database, world “land under permanent meadows and pastures” was equal to 3.2 billion ha in “2010”, including 145 million ha in West Africa and 551 million ha in ECS Africa. These estimates are consistent with those of Ramankutty et al. (2008) established for the year 2000 (3.15 billion ha). However, Mottet *et al.* (2017) deduced from their pastureland estimate of 3.5 billion ha about 1.5 billion ha they considered as not really supporting livestock activities. For their part, Henderson *et al.* (2015) estimated that world pasture areas were equal to 2.6 billion in a specific work that aimed at better conciliating FAOStat and GAEZ data while excluding areas “without livestock”. These reductions in initial pastureland areas should not be misunderstood to mean that the technical infeasibility of our scenarios would be automatically aggravated. This because other livestock supply parameters and variables should be adjusted accordingly – by increasing pasture grazing intensities and/or decreasing forage-to-output ratios – to re-establish the consistency of the biomass model for the base period (**SM13**). Uncertainties surrounding estimates of permanent pasture areas are aggravated by the heterogeneity of permanent grassland cover definitions depending on the statistical source and/or the study. This can be illustrated by estimates of “global grassland cover or pasture areas” summarised in Erb *et al.* (2007) who reported figures for the year 2000 ranging from a minimum of 3.2 million ha up to a maximum of 6.8 billion ha.

5. Conclusion

Three main lessons can be highlighted. First, achieving healthy diets worldwide requires an analysis at regional level. Second, several regions of the world would be constrained by their maximum available cultivable areas including a no deforestation assumption. Third, pastureland needs would be high in several world regions and particularly in SSA even in a scenario assuming increases in grazing intensities, improvements in feed efficiencies, the substitution of red meat by white meat in healthy diets, and exogenous increases in import shares for dairy products, beef meat and meat of small ruminants. To diminish pastureland needs in 2050 and make our scenario technically feasible in SSA, other action levers must be mobilised, for example by sustainably increasing crop yields, irrigated areas and cropping intensities, increasing the share of concentrated feeds and quality forages in livestock rations, reducing food waste and losses, targeting regional healthy diets richer in plant proteins and poorer in animal proteins, or increasing imports from third countries. All the levers require research, innovation, investment, behaviour changes and strong public policies. This is all the more important that food demand should continue to increase after 2050 in a context where CC impacts on agricultural supply could be more negative, accompanied by more frequent extreme events.

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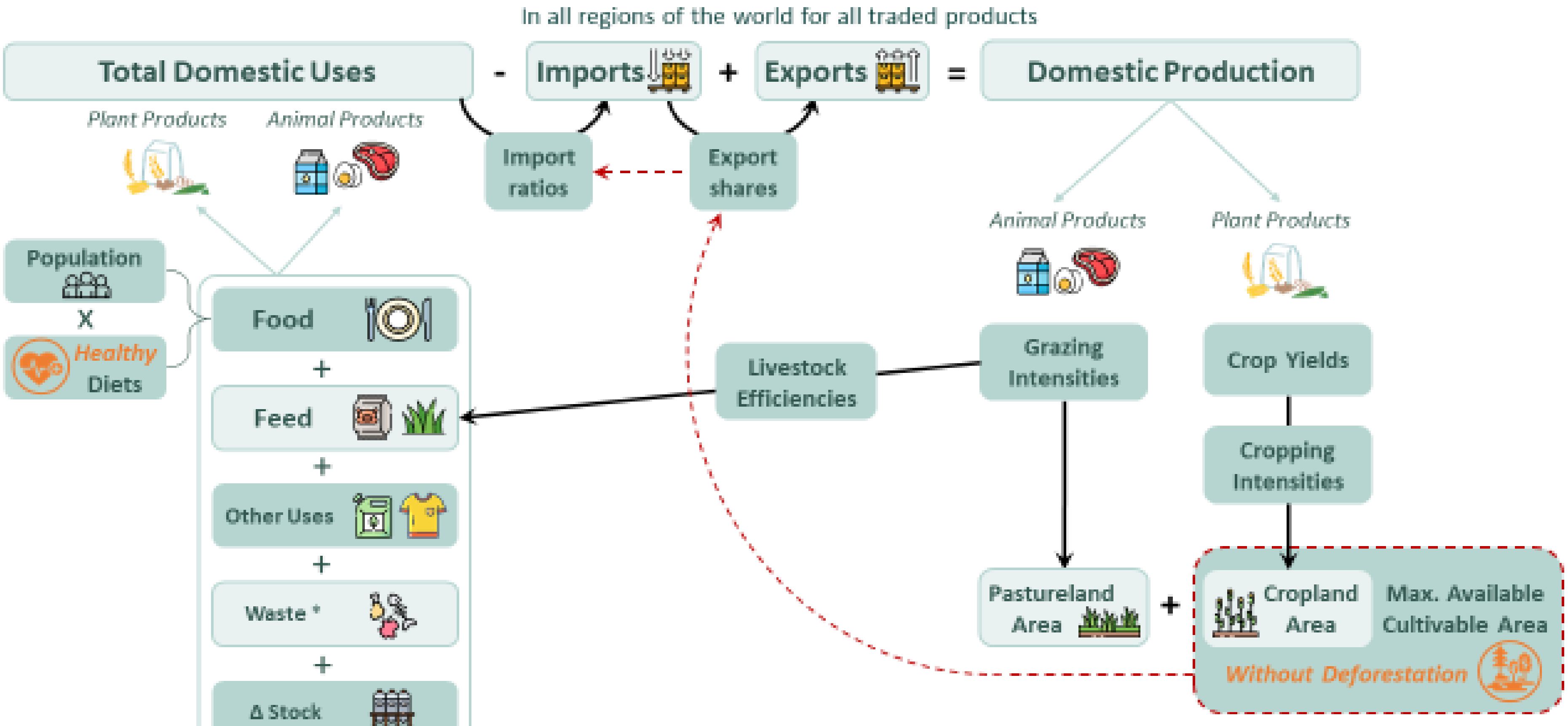
Figure 1. The modelling framework



In a given region, when Cropland Area > Max. Available Cultivable Area: decrease of the regional export share and, if needed, increase of the regional import ratio

Legend: Variables and/or parameters are distinguished according to their status in the modelling framework : exogenous (dark green), endogenous (light green), subject to normative assumptions (orange). *: Waste and loss rates are exogenously fixed; their levels are endogenously determined from uses.

Table 1. Cropland need changes in 2050 induced by demand component evolutions (million ha)

	Cropland areas in "2010"	Changes in cropland areas in 2050 due to demand component evolutions							Cropland areas in 2050 due to demand effects
		Demography	Healthy diets			Uses for biofuels and other non-food uses	Total		
			Effect of the plant component of healthy diets	Effect of the animal component of healthy diets	Total		Million ha	%	
Europe	127	+12	+15	-13	+2	0	+14	+11%	141
Can-USA	193	+41	+14	-33	-19	+6	+28	+14%	221
Bra-Argentina	116	+22	+8	-6	+1	+12	+35	+30%	151
Rest of Am.	69	+19	+10	0	+10	+1	+30	+43%	99
FSU	202	+23	+13	-9	+4	+1	+28	+14%	230
China	123	-1	0	-2	-2	+1	-2	-1%	121
India	169	+53	+62	+19	+82	0	+135	+80%	305
Rest of Asia	172	+52	+26	+2	+28	+4	+84	+49%	256
NME	57	+27	+8	-1	+7	0	+34	+60%	91
North Africa	28	+18	+8	+1	+9	0	+26	+92%	54
West Africa	99	+128	+10	+64	+75	+2	+205	+208%	303
ECS Africa	134	+151	+72	+29	+101	0	+253	+189%	387
Oceania	48	+17	+10	-5	+5	0	+22	+46%	70
ROW	2	0	0	0	0	0	0	0%	0
Total World	1,539	+562	+256	+47	+303	+27	+892	+58%	2,431

Table 2. Cropland need changes in 2050 (million ha) under the combined effects of demand and supply component evolutions, including the land constraint linked to maximum available cultivable areas In 2050 and the normative assumption of no deforestation between "2010" and 2050

Panel a. 'Moderate' growth of crop yields

Regions	Cropland areas in "2010" (million ha) [0]	Changes in 2050 due to demand and supply effects (million ha)					Sum in 2050 of demand and supply effects (million ha) [1]+[2]	Additional cropland needs in 2050 with the land constraint: SI > 40 and no deforestation ****		Cropland areas in 2050 with the land constraint (million ha) [0] + [3]		Maximal cultivable areas in 2050 with the land constraint (million ha)
		Demand effects [1] *	Supply effects: Supply components and total									
			AE **	Crop yield effects due to		Total [2]		Million ha [3]	%			
				CC ***	TD ***							
Europe	127	+14	+1	+5	-27	-20	-6	+14	+11 %	141	<	199
Can-USA	193	+28	+2	+10	-40	-28	0	+21	+11 %	214	<	497
Bra-Arg.	116	+35	+2	+5	-42	-36	-1	+10	+9 %	126	<	360
Rest of Am.	69	+30	-1	+4	-31	-28	+2	+8	+11 %	77	<	189
FSU	202	+28	-11	+7	-70	-74	-46	-37	-18 %	165	<	380
China	123	-2	+11	+4	-27	-14	-14	-11	-9 %	112	<	176
India	169	+135	+9	+9	-101	-83	+52	+22	+13 %	191	=	191
Rest of Asia	172	+84	-1	+6	-79	-74	+9	+1	+0.5 %	173	=	173
NME	57	+34	0	0	-25	-24	+10	-5	-10%	52	=	52
North Afri.	28	+26	+1	+1	-15	-13	+14	-15	-51 %	14	=	14
West Afri.	99	+205	-2	+13	-98	-87	+118	+83	+84 %	182	=	182
ECS Africa	134	+253	-3	+17	-127	-113	+140	+145	+108 %	279	<	618
Oceania	48	+22	-1	+3	-19	-17	+5	+15	+31 %	63	<	72
ROW	2	+0.4	-0.1	+0.1	-0.7	-0.7	-0.3	-0.1	-2%	2.2	<	2.9
World	1,539	+892	+7	+84	-701	-610	+282	+251	+16 %	1,790	<	3,105

Panel b. ‘High’ growth of crop yields

Regions	Cropland areas in “2010” [0]	Changes in 2050 due to demand and supply effects (million ha)					Sum in 2050 of demand and supply effects (million ha) [1]+[2]	Additional cropland needs in 2050 with the land constraint: SI > 40 and no deforestation ****		Cropland areas in 2050 with the land constraint (million ha) [0} + [3]		Maximal cultivable areas in 2050 with the land constraint (million ha)
		Demand effects [1] *	Supply effects: Supply components and total (million ha)									
			AE **	Crop yield effects due to		Total [2]		Million ha	%			
				CC ***	TD ***							
Europe	127	+14	+1	-3	-33	-34	-20	-11	-9 %	116	<	199
Can-USA	193	+28	+2	+0	-58	-55	-28	-18	-9 %	175	<	497
Bra-Arg.	116	+35	+2	-4	-37	-39	-4	-1	0 %	116	<	360
Rest of Am.	69	+30	-1	-1	-26	-28	+2	+4	+6 %	73	<	189
FSU	202	+28	-11	-4	-85	-101	-73	-68	-34 %	134	<	380
China	123	-2	+11	-3	-29	-21	-23	-21	-18 %	101	<	176
India	169	+135	+9	-8	-107	-107	+28	+22	+13 %	191	=	191
Rest of Asia	172	+84	-1	-9	-64	-74	+10	+1	0 %	173	=	173
NME	57	+34	0	-5	-28	-33	+1	-5	-10 %	52	=	52
North Afri.	28	+26	+1	-2	-20	-21	+5	-15	-51 %	14	=	14
West Afri.	99	+205	-2	-1	-149	-152	+53	+55	+56 %	153	<	182
ECS Africa	134	+253	-3	-1	-181	-184	+68	+70	+52 %	204	<	618
Oceania	48	+22	-1	-1	-12	-14	+8	+13	+27 %	61	<	72
ROW	2	+0.4	-0.1	-0.1	-0.5	-0.7	-0.2	-0.1	-5%	2.2	<	2.9
World	1,539	+892	+7	-42	-830	-865	+27	+25	+2 %	1,565	<	3,105

Notes. Reading key: Relatively to “2010” levels, in the case of ‘moderate’ growth of crop yields, world cropland needs would increase by +892 million ha in 2050 because of demand effects but would decrease by -610 million ha because of supply effects, resulting in a net increase of needs of +282 million ha. The net increase in cropland needs would be equal to +251 million ha (+16 %) with respect to “2010” levels when the land constraint is introduced (cultivable land classes with a SI > 40 and no deforestation) resulting in world cropland areas in 2050 equal to 1,790 million ha, a figure that is inferior to the world maximal cultivable area (SI > 40) with no deforestation (3,105 million ha). *: From Table 1. **: AE for animal efficiencies (effects of AE evolutions were evaluated using “2010” crop yields, that is without taking into account crop yield improvements in 2050 that would reduce cropland areas used for animal feed, other things being equal). ***: CC and TD measure the effects on crop yields of climate change (CC) and technological developments (TD), respectively. ****: Maximum available cultivable land area in 2050 (SI > 40) with no deforestation with respect to “2010” (see SM9).

Table 3. Agricultural land needs (cropland and pastureland) in 2050 (million ha)

Panel a. 'Moderate' growth of crop yields

	Total emerged areas (GAEZ) [1]	Areas in "2010"			2050				
		Crops (FAO) [2]	Pastures (FAO) [3]	Forests and other "uses" (GAEZ) [4]	Cropland areas [5] *	Pastureland needs [6]	Areas available for pastures without farmland expansion between "2010" and 2050 [7]=[2]+[3]-[5]	Technical infeasibility without farmland expansion ([6]>[7])	Agricultural areas exceeding total emerged areas ([5]+[6]>[1])
Europe	477	127	72	279	141	62	57	**YES**	
Can.-USA	1,738	193	265	1,280	214	220	244		
Bra.-Argent.	1,106	116	304	685	126	321	294	**YES**	
Rest of Am.	899	69	254	577	77	327	246	**YES**	
FSU	2,050	202	363	1,485	165	277	400		
China	874	123	393	359	112	389	404		
India	296	169	10	116	191	16	11	**YES**	
Rest of Asia	839	172	168	499	173	248	167	**YES**	
NME	587	57	243	287	52	292	249	**YES**	
North Africa	545	28	59	458	14	55	73		
West Africa	499	98	145	256	182	695	61	**YES**	**YES**
ECS Africa	1,893	134	551	1,198	279	2,100	406	**YES**	**YES**
Oceania	841	48	371	422	63	501	356	**YES**	
ROW	32	2	2	27	2	2	2		
Total World	12,665	1,539	3,199	7,927	1,790	5,505	2,498	**YES**	

Panel b. ‘High’ growth of crop yields

	Total emerged areas (GAEZ) [1]	Areas in “2010”			2050				
		Crops (FAO) [2]	Pastures (FAO) [3]	Forests and other “uses” (GAEZ) [4]	Cropland areas [5] *	Pastureland needs [6]	Areas available for pastures without farmland expansion [7]=[2]+[3]-[5]	Technical infeasibility without farmland expansion ([6]>[7])	Agricultural areas exceeding total emerged areas ([5]+[6]>[1])
Europe	477	127	72	279	116	55	83		
Can.-USA	1,738	193	265	1,280	175	205	283		
Bra.-Argent.	1,106	116	304	685	116	295	305		
Rest of Am.	899	69	254	577	73	302	249	**YES**	
FSU	2,050	202	363	1,485	134	258	431		
China	874	123	393	359	101	365	414		
India	296	169	10	116	191	16	11	**YES**	
Rest of Asia	839	172	168	499	173	232	167	**YES**	
NME	587	57	243	287	52	288	249	**YES**	
North Africa	545	28	59	458	14	86	73	**YES**	
West Africa	499	98	145	256	153	783	90	**YES**	**YES**
ECS Africa	1,883	134	551	1,198	204	1,960	481	**YES**	**YES**
Oceania	841	48	371	422	61	420	358	**YES**	
ROW	32	2	2	27	2	1	2		
Total World	12,665	1,539	3,199	7,927	1,565	5,267	3,171	**YES**	

Notes. *: From Table 2, panel a for ‘moderate’ yield growth and panel b for ‘high’ yield growth.

Table 4. Sensitivity analysis of cropland and pastureland needs by 2050 in SSA (million ha)

Panel a. West Africa

West Africa	"2010"	2050				
		Baseline *	Variants **			
			[1] +30 % in GI	[2] = [1] & +20 % in FE ***	[3] = [2] & meat substitution	[4] = [3] & ruminant import shares = 0.35
Cropland needs	98	153	153	147	142	139
Pastureland needs	145	783	620	514	273	216
Farmland needs	243	937	773	661	415	355
Farmland needs in 2050 in excess of "2010" farmland	-	+694	+530	+418	+172	+112

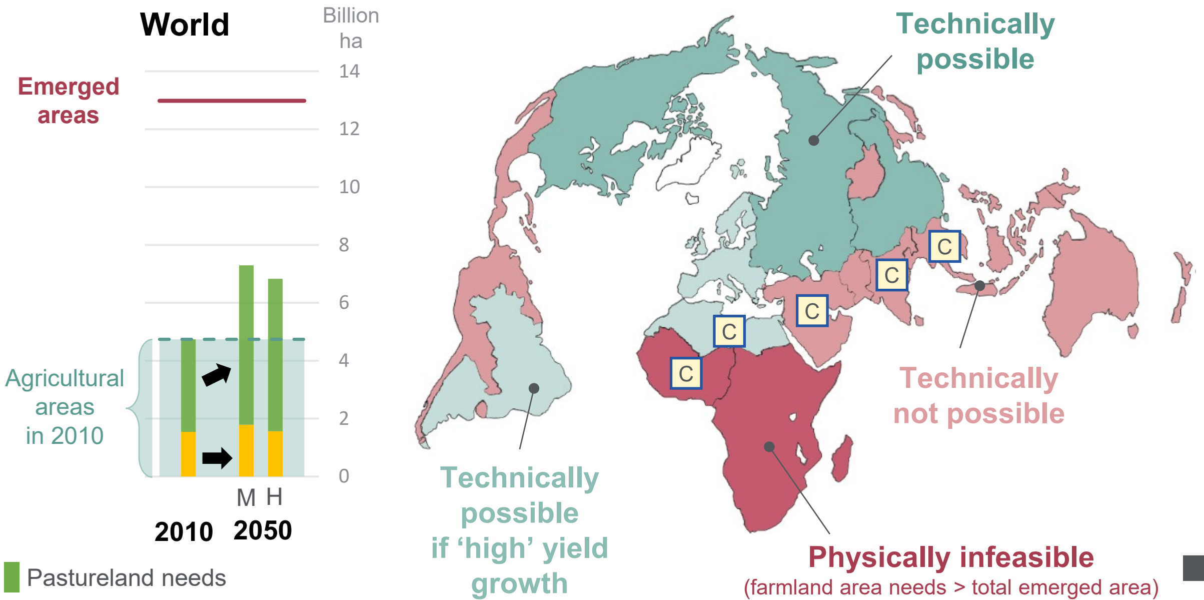
Panel b. ECS Africa

ECS Africa	"2010"	2050				
		Baseline *	Variants **			
			[1] +30 % in GI	[2] = [1] & +20 % in FE ***	[3] = [2] & meat substitution	[4] = [3] & ruminant import shares = 0.35
Cropland needs	134	204	204	202	204	199
Pastureland needs	551	1,960	1,551	1,321	981	683
Farmland needs	685	2,164	1,755	1,523	1,185	881
Farmland needs in 2050 in excess of "2010" farmland	-	+1,480	+1,070	+838	+500	+197

*: Baseline and variant scenarios simulated assuming a 'high' growth of crop yields. **: Variant [1]: +30% of grazing intensities in all world regions; Variant [2]: Variant [1] & +20 % of ruminant feed efficiencies in SSA; Variant [3]: Variant [2] & substitution of red meat by white meat in SSA; for more details, see text; Variant [4]: Variant [3] & increases in import shares of ruminant meat and dairy products up to the 2050 import share of dairy products in West Africa (0.35) implying increases in West Africa of +272% (+0.7 million tonnes) and + 2.474% (+0.7 million tonnes) for respectively beef meat and meat of small ruminants, and increases in ECS Africa of +570% (+31,6 million tonnes), +1,300% (+2,8 million tonnes) and +1,594% (1.1 million tonnes) for respectively dairy product, beef meat and meat of small ruminants. ***: The two assumptions of the second variant are consistent in the sense where higher grazing intensities will likely increase the nutritional value of pastures with in particular more legumes; one can thus expect quicker livestock growth rates, notably if sanitary issues are jointly best managed, and finally higher feed efficiencies if farmers agree to sell younger finished animals and to retain less non-breeding animals.

Can healthy diets be achieved worldwide in 2050 without farmland expansion?

- Focus on **food availability** taking into account the effects of **climate change** and **technical developments** on agricultural productivity
- **Cropland** and **pastureland** needs in 2050 estimated under:
  - The assumption of **healthy diets** and **no farmland expansion**
  - Two sets of **crop yield** projections (‘**moderate**’ and ‘**high**’ growth)
- Regional and global analysis using a **biomass balance model**



🟩 Pastureland needs

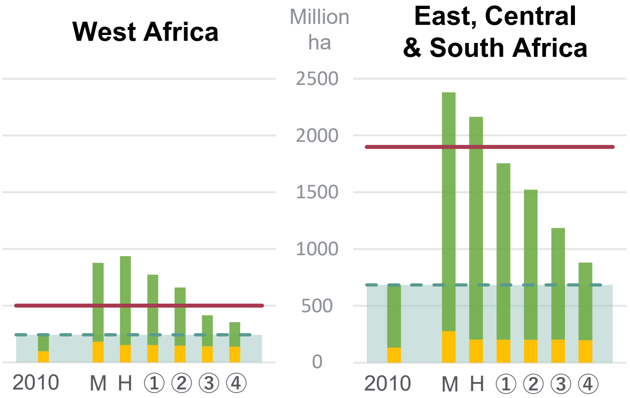
🟨 Cropland needs

M: ‘Moderate’ yield growth

H: ‘High’ yield growth

C Regions that would be constrained in 2050 by maximum cultivable areas with no deforestation (in the case of ‘moderate’ yield growth for West Africa)

Impacts of additional levers on total farmland needs in Sub-Saharan Africa



① = ‘High’ yields + ↗ **grazing intensity**

② = ① + ↗ **animal feed efficiency**

③ = ② + **meat substitution**

④ = ③ + ↗ **ruminant import shares**