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Socio-economic trajectories, urban area expansion and ecosystem conservation affect global potential supply of bioenergy

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ABSTRACT

Biomass energy is projected to be a critical resource for defossilization of the energy system. While urban area extension and land conservation would constrain potential biomass supply, there is little understanding of their impacts. This paper presents global and regional bioenergy supply potential estimates by newly implementing urban area expansion in an integrated assessment model AIM (Asia-Pacific Integrated Model). Scenarios were investigated as combinations of shared socio-economic pathways (SSPs) with default and expanded urban area and conservation. The bioenergy potentials in 2050 with fixed urban area at base year level were in the range of 228 (SSP3) to 292 (SSP1) exajoules per year (EJ yr-1), corresponding to differences in fraction of land available for bioenergy crop production. The bioenergy potentials under urban expansion closely tracked trends in the reference SSP cases, but with decreases ranging from 4.48 (SSP1) to 6.95 (SSP5) EJ yr-1. While global total effects were small, regions experienced mixed results and in some cases a reversal of trends. Under conservation scenarios, reductions in bioenergy potential caused by urban expansion were observed to be lower except in some regions and scenarios. These results enhance the understanding of SSP patterns of bioenergy potential while at the same time revealing how global trends may fail to capture region-specific trends. The study concluded that: 1) urbanization may lack relevance for bioenergy at the global scale but becomes important for some regions, 2) loss of bioenergy potential can be curbed by encouraging compact urbanization as in SSP1 (Sustainable Development), zoning, and pursuing joint energy-conservation policies.

1. Introduction

Climate change mitigation is a central theme of the sustainable development goals (SDGs) as it is the hallmark of sustainable development. For most developed countries, energy-related carbon dioxide (CO_2) emissions dominate a large share of Greenhouse gas (GHG) emissions, and so naturally, the main interests of climate change mitigation should be on energy system transformation. Most countries aim to reach carbon neutrality by 2050 or earlier, and bioenergy presents a good opportunity for short-term climate action, since it is readily available, storable and easily integrated with existing infrastructure [1]. While recent global climate change mitigation studies show that a large volume of bioenergy is required for realizing the so-called negative emissions, to attain 2 or 1.5 °C climate neutrality [2–4], bioenergy adoption at sizable scales can have several co-benefits including offering a flexible electricity generation option [5], improving soil, land restoration [6] and fostering rural development. This means that bioenergy deployment can contribute to the achievement of SDGs 2,7,13 and others [7]. In the International Energy Agency's (IEA) Net Zero by 2050 scenario, modern bioenergy use reaches 102 EJ in 2050 and bioenergy's share of electricity generation rises to 5% [8]. Therefore, land-use and energy systems are closely inter-linked, within the context of energy-related CO_2 emissions reduction. Moreover, for other countries, the share of agricultural or land-use related GHG emissions could be

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large, and consequently, land-use management would play a vital role in such countries for GHG emissions reduction [9–12]. The sustainability challenge seeks to balance competing land-uses to ensure sustained food supply, decent living conditions and improved mobility, all without harming biodiversity [13,14]. Biodiversity has recently been identified as one of the important areas when assessing global bioenergy for managing climate change [15,16].

Concern for biodiversity, which fuels strict protection policies, has the implication that the land suitable for biomass production now comes under protection [17]. The growing realization and identification of certain grassland areas as highly biodiverse [18] can lead to such areas being excluded from allocation to biomass production. Presently, only a limited portion of biodiversity is preserved by protected areas; but there are efforts to bring more land under protection [19]. Preference for biodiversity has also been reported in Integrated Assessment Models (IAMs), in cases where land available for production is scarce [20]. Some of the regions that have large areas classified (or potentially classified) as protected areas are also the regions where rapid urbanization is projected to occur, and these are mostly middle-income countries [21]. Incidentally, most times conservation actions happen in human-dominated matrices; since people tend to settle in natural landscapes that are biologically rich [22]. Therefore, urban expansion coupled with conservation poses a threat to biomass supply. The exclusion of degraded land from productive use can also further reduce land available for biomass production [17]; and although there have been suggestions to use degraded areas for biomass production [23], only a percentage of these areas may be applied to such production.

So far, biodiversity and soil conservation have been considered in some bioenergy assessment studies [17], but without accounting for the effects of other factors such as urban area expansion. Expansion of urban area can affect biomass supply through direct land cover change. Urbanization is a land use type that results from population growth and economic expansion (where land is required for settlement or industrial activity). One of the most evident changes in recent years is the rapid change from rural to peri-urban and urban areas that occurs through the built environment. Some of the rapidly growing regions in terms of urbanization are India, the EU, the US and China [24,25]. Recent projections [25] show that this trend is likely to continue to the end of this century regardless of the socioeconomic assumptions represented by shared socio-economic pathways (SSPs) [26], even in regions where population is projected to decline. The SSPs are plausible ways in which the world will evolve, presented as narratives and quantified measures of development without accounting for climate change [27].

The five SSPs are separated by two axes, one implying challenges to mitigation and the other, challenges to adaptation [26–28]. The primary difference among SSPs lies in their assumptions on population, education, Gross Domestic Product (GDP) and economic development [29]. SSPs 1, 2 and 5 describe comparatively more equitable worlds, with lower challenges for adaptation but differing challenges for mitigation. Rapid economic growth in SSP5 leads to high energy demand. This, combined with heavy reliance on fossil fuels, leads to high mitigation challenge. The demand for bioenergy is also high in SSP5, estimated at 480 EJ per year (EJ yr-1) by 2100 [30]. Like SSP5, SSP3 also relies on fossil fuels but has high challenges to both mitigation and adaptation [26]. The main difference between SSP3 and 5 is the pace of growth [30]. Projected energy demand in SSP4 is lower relative to SSP2. The sustainability narrative (SSP1) has low challenges to both mitigation and adaptation due to low population growth and emphasis on green technologies. Even though SSPs have been criticized as lacking a structure to guide their implementation [31], they still remain to be the best scenarios so far describing possible development trajectories of our world in this century.

As the world considers the move towards reliance on large-scale bioenergy, more assessments are required on the feasibility of proposals, taking into consideration all possible future scenarios. The use of dedicated bioenergy crops is required to complement current resources (mostly crop residues which are limited and their removal would cause soil degradation [6]) and help to meet the projected increased demand for bioenergy [32,33]. Although the main concerns with bioenergy are related to dedicated energy crops, synergies can be found for climate action and other SDGs in using marginal and abandoned lands for production [34]. According to recent estimates, 154 EJ yr-1 of bioenergy median supply will be required in 2050 to cap warming at 1.5 °C [35]. Globally, modern bioenergy made up about 5.1% of total energy consumption in 2018 [36]. Factors that determine bioenergy potential are such as: yield efficiency (technology) [37,38], costs [39], climate change, policies (e.g environmental), integration (industry involvement to create demand), timeframe (can lead to higher potential due to assumed land availability and higher yields in the long-term) and land availability [40]. Some supply-chain drivers such as change in dietary habits, waste management and population are also among top factors determining the potential availability of biomass [41].

Currently, there is no study that estimates bioenergy potential with consideration of urban expansion, biodiversity conservation, and rehabilitation of degraded land. This study therefore aims to estimate biomass supply under different socio-economic assumptions including urban area projections [25] using the Asia-Pacific Integrated Model/Platform for Land-Use and Environmental Model (AIM/PLUM) [42]. This study adds value to the existing literature [17], whereby in addition to conservation, an assessment of urban area expansion impact on bioenergy potential in conjunction with SSP variations is undertaken.

2. Methods

2.1. Model used and settings

A flowchart of the modeling exercise is shown in Fig. 1. The AIM/PLUM land-use spatial allocation (downscaling) model used in this study employs a profit maximization and land competition approach where land-use is determined by factors such as cost of production and yield potential, taking land-use policies into account. The future cropland and afforestation for example, are allocated based on the highest return under a given productivity. The model uses a reference land-use map [42,43] that integrates cropland areas based on [44] while other land-types are drawn from Hurtt et al. (2011). Starting from the reference year, the allocations in preceding years are fed into future years. The distinguished land types in AIM/PLUM output are croplands, pasture, forests (managed and unmanaged), grasslands, inland water areas and built-up land. SSP-based population densities, GDP and carbon prices are some factors incorporated in the model, where for instance croplands cannot expand to extremely low density areas. Other factors affecting land-use decisions, such as infrastructure, are implicitly considered using population density. Initial aggregate land demand, GDP, total population regional estimates, land-use change emissions, and volumes, values and prices of commodities are drawn from the AIM/Hub Model (formerly named AIM/CGE) [43,46]. AIMPLUM has previously been verified using the crop and pasture land-use types [42] and applied in biomass estimation [17]. In this study, similar to previous studies [17,47], land for biomass production from second generation energy crops is estimated from light forest and grasslands. Model parameters to estimate biomass were validated in a previous study using yield data for switchgrass and miscanthus [17], under the SSP2 pathway.

AIM/PLUM can simulate the impact of urban area expansion on other land-use types because it is spatially explicit. During the iterative sequential downscaling process, urban land fraction is treated as an exogenous variable (not calculated within the model) and given priority allocation, together with inland water bodies. Thus, urban area fraction can easily be updated; and any other allocations are made on the remaining portion of land. The model also treats protected land fraction as an exogenous input, since protected areas should basically not be allocated to other land uses. In this sense, protected areas would also

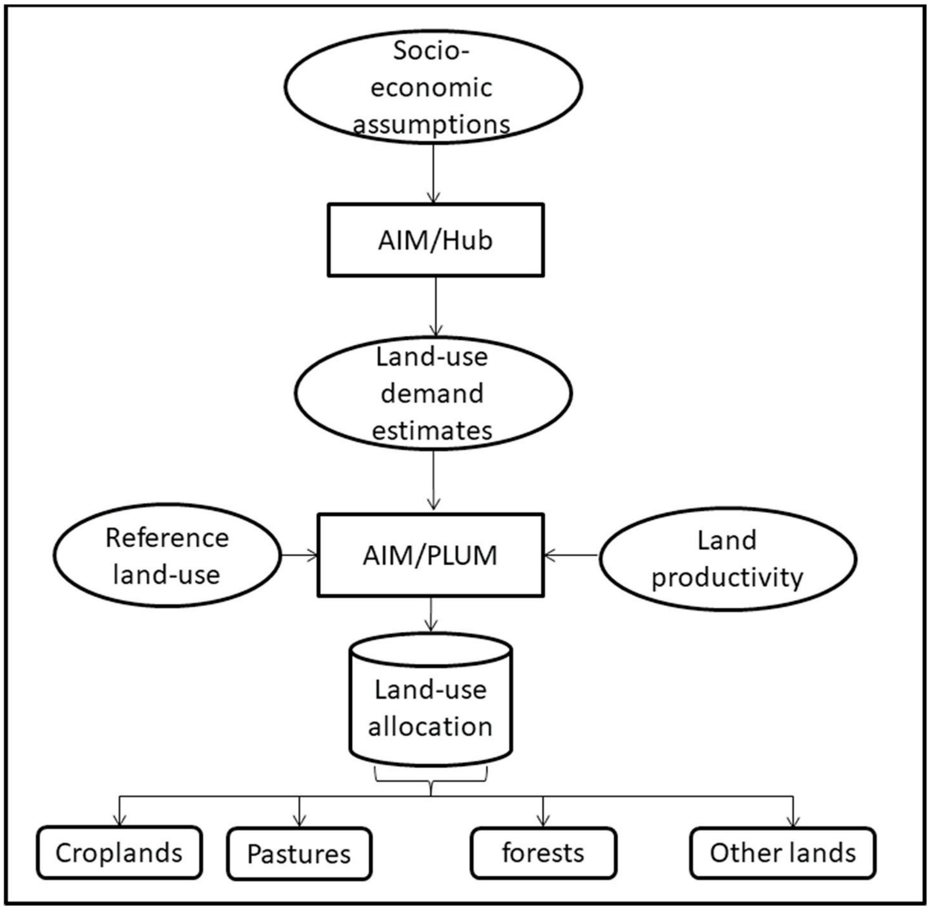

Fig. 1. A flowchart of the model used showing inputs and outputs.

limit land available for other land-uses, including bio cropland. In the model, the year 2005 is set as the base year and all other years are projected based on a 10-year time-step from 2010 to 2100. Model resolution is 0.5°; therefore land-use changes are modelled at a regular latitude-longitude grid.

2.2. Scenarios

To explore the impacts of urban area expansion and ecosystem conservation on bioenergy potential, scenarios were developed as shown in Table 1 where the scenarios estimated biomass supply every decade from 2020 up to the year 2050. Urban area expansion effect on bioenergy potential was studied across the 5 SSPs under the assumption of no climate change. For each reference case, urban area was retained at base year level, while in the urban expansion cases urban area was updated every decade based on SSP projections. Total technical bioenergy potentials were then compared between reference and alternative cases. Although urban area affects other land-uses through both physical displacement/substitution and non-spatial activities that take pace in the urbanized area, this analysis only assessed the spatial changes in urban area and corresponding change in bioenergy cropland area and resultant potential change in bioenergy supply at global and regional levels.

To estimate the impact of conservation policies, default and strong protection cases were studied (Table 1). Default protection policy is where only zoned areas continue to be protected while strong protection entails both conservation of protected areas and restoration of degraded areas.

Table 1
Model settings.

Scenario	Socioeconomic assumption	Urban area	Ecosystem conservation
SSPX + Ref	SSP1, 2, 3, 4 or 5	Retained at base year level	Default protection
SSPX + UrbExp	SSP1, 2, 3, 4 or 5	Expansion at SSPX level	Default protection
SSPX + Ref + Conservation	SSP1, 2, 3,4 or 5	Retained at base year level	Protection & rehabilitation
SSPX + UrbExp + Conservation	SSP1, 2, 3, 4 or 5	Expansion at SSPX level	Protection & rehabilitation

2.3. Dataset

Urban area fraction data used in the reference cases was for the year 2005 and was based on historical trends [45] while that for future years was based on SSP projections [25]. The SSP-based data mapped at 0.25° resolution was obtained online [48] and aggregated to 0.5° for input to AIM/PLUM. In the urban expansion cases (Table 1), urban area projections for the year 2010 were assumed for the base year. Future projections show global urban expansion under SSP5 to be very high, doubling that of SSP1 by 2060 (Fig. 2). The SSPs are divergent in their urbanization rates, with SSP 2 and SSP4 showing almost similar but higher rates than SSP 1 and SSP3. Low rates of urban expansion in SSP1 are associated with environmental consciousness and hence a lack of need while those in SSP3 are associated with a lack of means, due to paralysed economic growth.

On top of the difference in base year among datasets, another discrepancy arose from the difference in definitions of urban area. While the historical urban area data was mapped based on populated areas, the SSP-based urban projections utilized national inventories and satellite

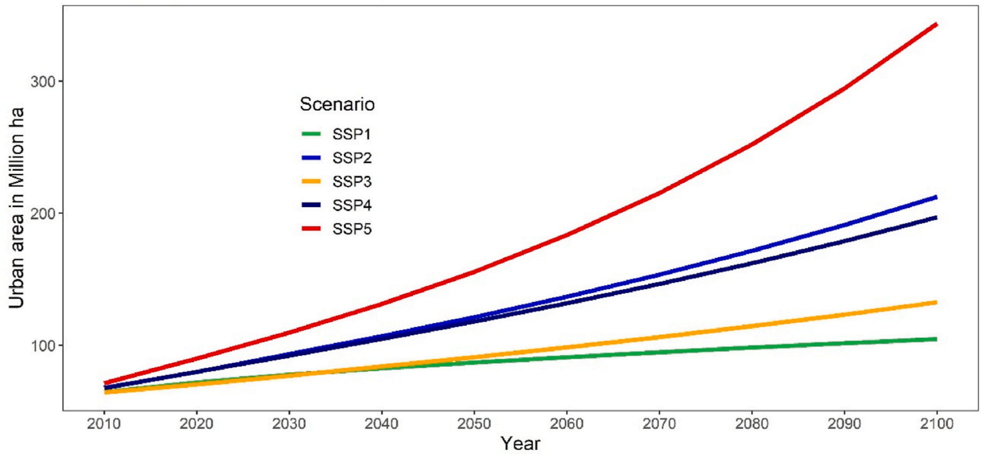

Fig. 2. Global future projected urban area trend across SSPs based on [48].

images of urban layer that included all man-made surfaces. This led to a slight difference in the number of grids with urban fraction between the two inputs. Since the analysis did not attempt to harmonize the two datasets, additional urban fraction in the SSP-based data is referred to as "expanded urban area" instead of "urban area growth/increase"; because growth has the connotation that existing proportions are increased in size. Settlements are complex in both space and time and since there is a general lack an internationally accepted standard definition of urban areas, definitions can vary from country to country. However, the analysis was set up with the belief that the current implementation is robust enough to capture the objective of this study. Moreover, to properly represent the impact of urban area expansion, analysis was done across all SSPs (which represent different possible directions of urban area growth - minimal, normal, extreme) as shown in Table 1.

Details on protected areas used in this study can be found in Refs. [17,49,50]. These areas were fully restricted from changing to other land types, to protect biodiversity.

3. Results

3.1. Potential land area for bioenergy supply

3.1.1. Global potential bioenergy crop area and its changes due to urban expansion and conservation

Global potential bioenergy cropland areas under each scenario in 2050 are shown in Table 2. Rates of loss due to urban expansion, land protection and a combination of the two relative to the reference cases are shown beneath the land area estimates. The table shows that there will be more land available for biomass production under a sustainability scenario (SSP1Ref and SSP1UrbExp). A middle-of-the-road (SSP2Ref and SSP2UrbExp) and regional rivalry (SSP3Ref and SSP3UrbExp) scenarios will have slightly less potential bioenergy cropland areas than a fossil-fueled development scenario (SSP5Ref and SSP5UrbExp). This is likely due to higher population and lower GDP in the two scenarios, translating to higher agricultural land demand and decrease in lands available for biomass production. This result is consistent with reports of increased risk to food security with land transition to bioenergy in pathways with high population and low income [6]. Ecosystem conservation will lead to very high reduction of potential bioenergy cropland area (last two columns of Table 2). In scenarios with high adaptation challenges (SSPs 3 and 4), ecosystem conservation reduced the impact of urban expansion on availability of bioenergy cropland area.

Table 2
Estimated bioenergy cropland area in each socio-economic pathway under default, urban expansion and land protection scenarios in millions of hectares. Values below represent percentage loss relative to reference bioenergy cropland area.

Scenario	Area under reference scenario (SSPXRef)	Area under urban expansion (SSPXUrbExp)	Area under land protection scenario (SSPXRef + Conservation)	Area under protection and urban expansion (SSPXUrbExp + Conservation)
SSP1	1526	1512	1266	1257
		0.9	17	18
SSP2	1388	1366	1105	1084
		1.6	20	22
SSP3	1278	1261	1012	1012
		1.3	21	22
SSP4	1448	1429	1183	1183
		1.3	18	19
SSP5	1406	1380	1140	1140
		1.8	19	21

3.1.2. Regional potential area and its changes due to urban expansion and conservation

At the regional level, lower potential bioenergy crop areas can be expected under SSP1Ref relative to SSP2Ref in Canada, the EU, the US, Oceania and Brazil (Fig. 3, panel a). These regions have their highest bioenergy crop areas under SSP2. In Japan, bioenergy crop area in SSP1Ref was lower than all other SSPs, except SSP2Ref which had the least amount of land. Only Japan had less land in SSP1Ref relative to SSP3Ref and both Japan and Canada had less land in SSP1Ref relative to SSP5Ref. The highest bioenergy crop area for Japan was observed under SSP5Ref. This result implies that by pursuing sustainability (SSP1Ref), bioenergy potential in the named regions may be lowered relative to other development pathways, due to land availability constraint. Bioenergy crop areas reduced under urban expansion, but SSP trends closely tracked the reference cases. The rate of decline of bioenergy cropland area due to urban expansion relative to reference was generally lower in the SSP1 pathway. The greatest decline of 20% was observed in Japan under the SSP2 pathway. This is partly due to the lower initial potential area in Japan SSP2Ref.

Land protection caused larger reduction of bioenergy crop land relative to the reference scenarios, especially in the EU, with 53% (SSP3Ref + Conservation), 49% (SSP5Ref + Conservation), 48% (SSP2Ref + Conservation), 47% (SSP1Ref + Conservation) and 42% (SSP4Ref + Conservation) contraction. This large impact in the EU is apparent from the graph (Fig. 3, panel b) where the potential bioenergy crop area for the EU becomes lower than that of Oceania, India and South-East Asia. Urban area expansion was observed to further drive reductions in the EU by between 3% (SSP1UrbExp + Conservation) and

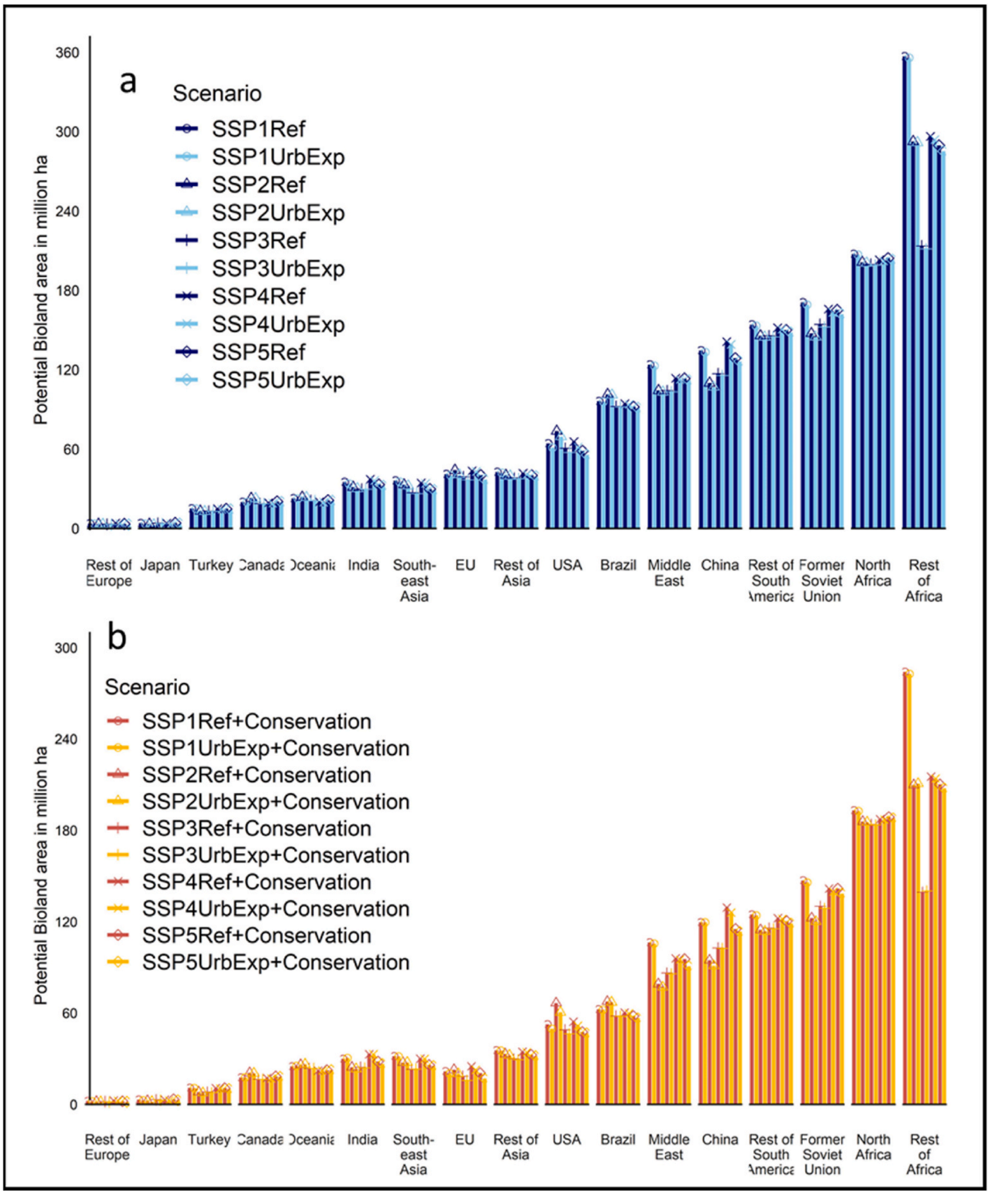

Fig. 3. Regional bioenergy crop areas across SSPs. **Panel a.** regional bioenergy potentials in reference and urban expansion scenarios without conservation. **panel b**. regional bioenergy potentials under conservation. Reddish and bluish colors indicate with and without conservation scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

9% (SSP5UrbExp + Conservation). The rest of Europe, Turkey, Brazil, Japan, Middle East and India were also highly impacted by conservation and may be expected to lose 43%, 38%, 33%, 25%, 24% and 22% of bioenergy crop area respectively in the SSP2Ref + Conservation scenario. Urban expansion will aggravate these reductions by a range of 0.5% (Brazil) −18% (Japan). In mid-century, under both urban expansion and conservation, a regional rivalry development pathway (SSP3UrbExp + Conservation) presents the greatest challenge to bioenergy cropland availability in the European continent, by causing a massive loss of 60% in the EU and 50% in the rest of Europe. In both cases, urban expansion contributes 7% loss. The least loss of bioenergy crop area to urban expansion was registered in Canada under SSP1. The regional potential bioenergy crop area distributions given urban expansion and ecosystem conservation are displayed in Fig.A1.

3.2. *Potential bioenergy*

3.2.1. *Global potential bioenergy supply and its changes due to urban expansion*

In the reference SSPs, global bioenergy potentials in 2050 were 292 EJ yr-1 EJ yr-1, 277 EJ yr-1 EJ yr-1, 228 EJ yr-1, 279 EJ yr-1 and 259 EJ yr-1 respectively, as shown in Fig. 4. In all years, the highest potential was registered in SSP1. Urban expansion (light blue bars) reduced bioenergy potentials to 288 EJ yr-1, 271 EJ yr-1, 223 EJ yr-1, 274 EJ yr-1 and 252 EJ yr-1 respectively. These declines are illustrated by the "SSPX + urbExp" bar graphs in Fig. 4. The figure also shows rates of loss across the scenarios in red dots. Lowest rate in SSP1 is because of the projected modest growth of urban area under this scenario. A fossil-fueled development pathway (SSP5) has the greatest rate of loss due to higher urban area expansion.

Enforcing protection policies that target protected areas and rehabilitation of degraded areas reduced bioenergy potential (orange bars in Fig. 4) by 96 EJ yr-1 on average. The highest rate of reduction of

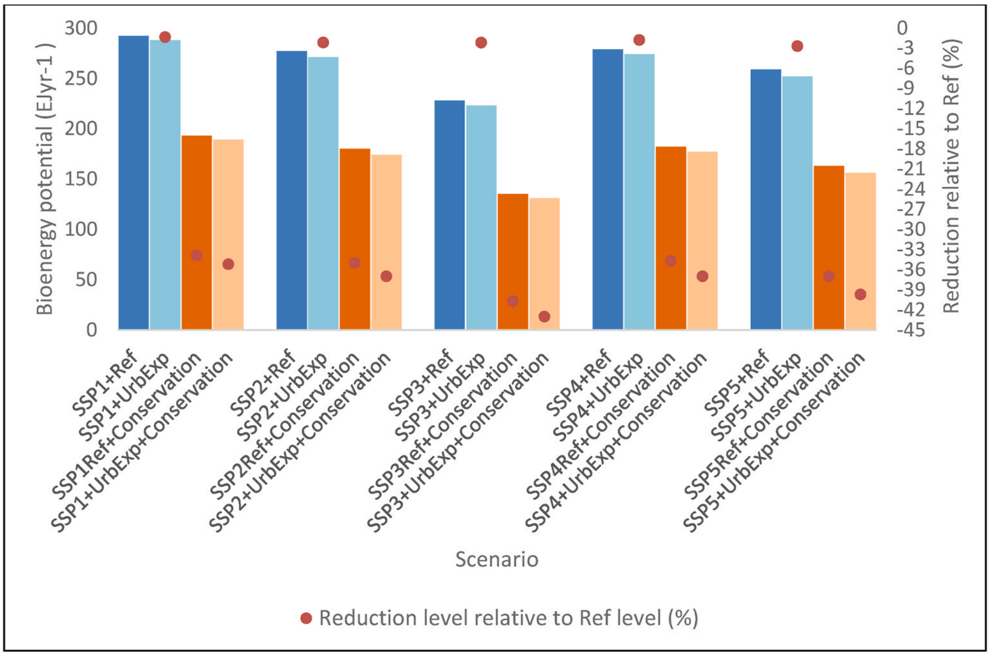

Fig. 4. Bioenergy potentials in Reference, urban expansion and conservation scenarios across SSPs. Bars and points show bioenergy potential (left axis) and relative reduction levels compared with reference cases (right axis). Reddish and bluish colors indicate with and without conservation scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

bioenergy potential by conservation was registered in SSP3Ref, partly due to the lower initial potential. When urban expansion was considered (SSPXUrbExp + Conservation), average reduction of bioenergy potential increased to 102 EJ yr-1.

3.2.2. *Regional potential bioenergy supply and its changes due to urban expansion*

At the regional level, in reference cases, results for 2050 showed that Brazil, rest of South America and rest of Africa were the biggest potential suppliers of bioenergy (Fig. 5), accounting for 72% of total bioenergy potentials in SSPs 1 and 5, 69% of total bioenergy potential in SSP2, 70% in SSP3 and 68% in SSP4. Urban expansion did not change these proportions. The proportional contribution to total potential bioenergy by the three regions was therefore relatively unaffected by the choice of socio-economic development pathway. Reductions in bioenergy potentials under a sustainability scenario (SSP1Ref) relative to SSP2Ref were observed in the US, Oceania, Brazil, Canada, and South East Asia. This is because except South East Asia, these regions had lower potential bioenergy crop areas under SSP1 (Fig. 3). The EU, Turkey, China, rest of south Asia, rest of south America, the former Soviet Union, middle East and Africa had their highest bioenergy potentials under SSP1, corresponding to the available bioenergy cropland. The exception, the EU, had highest bioenergy cropland area under SSP2. Bioenergy potential in the rest of Africa was severely impacted by an unequal development pathway (SSP3Ref), managing only 30 EJ yr-1, less than half the potential achieved under SSP1 (74 EJ yr-1). This was due to diminished available land for biomass production in SSP3Ref (Fig. 3). In Japan, India, rest of South America, Canada, Middle East and rest of South Asia, bioenergy potential was higher in SSP5 relative to SSP2. Except Canada and rest of Asia, these regions had higher bioenergy crop area in SSP5 relative to SSP2. Japan's bioenergy potential was highest under SSP5, corresponding with the higher potential bioenergy crop area. The US had a significant difference in potential bioenergy of 10 EJ yr-1 between SSP2Ref and SSP3Ref and 8 EJ yr-1 between SSP2Ref and SSP5Ref reflecting the relatively high difference in potential bioenergy crop area between SSP2Ref and the other two SSPs.

Urban expansion led to the reduction of potential bioenergy in all regions and scenarios except China under SSP1. Japan was among the most affected losing 9% (SSP1), 18% (SSP2), 11% (SSP3), and 14% (SSP4 and 5) bioenergy potential relative to reference. The high rate of loss under a middle-of-the-road development scenario (SSP2) is in part due to the lower reference bioenergy potential. The rest of Europe was severely impacted in SSPs 3 and 4 (12%) and 5 (17%). The US suffered a 10% loss under SSPs3 and 5 while North Africa suffered a 10% loss under SSP2. In SSP5, bioenergy loss due to urban expansion in the EU was 10%. Impact of urban expansion on the bioenergy potential of Brazil was low, averaging 0.5%. When conservation was factored, urban expansion impact on potential bioenergy in Japan increased to 12% in SSPs 1 and 3. Other regions whose urban expansion impact was aggravated by at least 2% under conservation include: the rest of South Asia (SSP1, SSP5), the rest of South America and Middle East (SSP2), the EU (SSP4) and Middle East (SSP5).

3.3. *Supply curve of bioenergy*

The SSP4Ref and SSP4UrbExp scenarios yielded the highest biopotential at low cost while SSP5Ref and SSP5UrbExp yielded the least (Fig. 6). At higher costs, SSP3Ref and SSP3UrbExp yielded the least bioenergy. In a highly unequal world with high population, slow growth rate and reliance on fossil fuels, higher costs may not be attractive for bioenergy production. At high costs, biopotential did not shift much within scenarios. When conservation was applied, potential was greatly diminished but the pattern of SSPs remained similar. At 5USD/GJ, in both reference and urban expansion, SSP 1, 2 and 4 protection scenarios, bioenergy yield was almost equal to that under SSP5Ref and SSP5UrbExp, reflecting the low potential of fossil-fueled (SSP5) development. Higher impact of urban expansion in SSP5 could be seen by the wider gap between SSP5Ref and SSP5UrbExp curves, relative to the other scenarios. The huge difference in bioenergy potentials between reference and conservation scenarios reflected the loss of land available for biomass production due to shrinkage of high-yield areas under conservation scenarios.

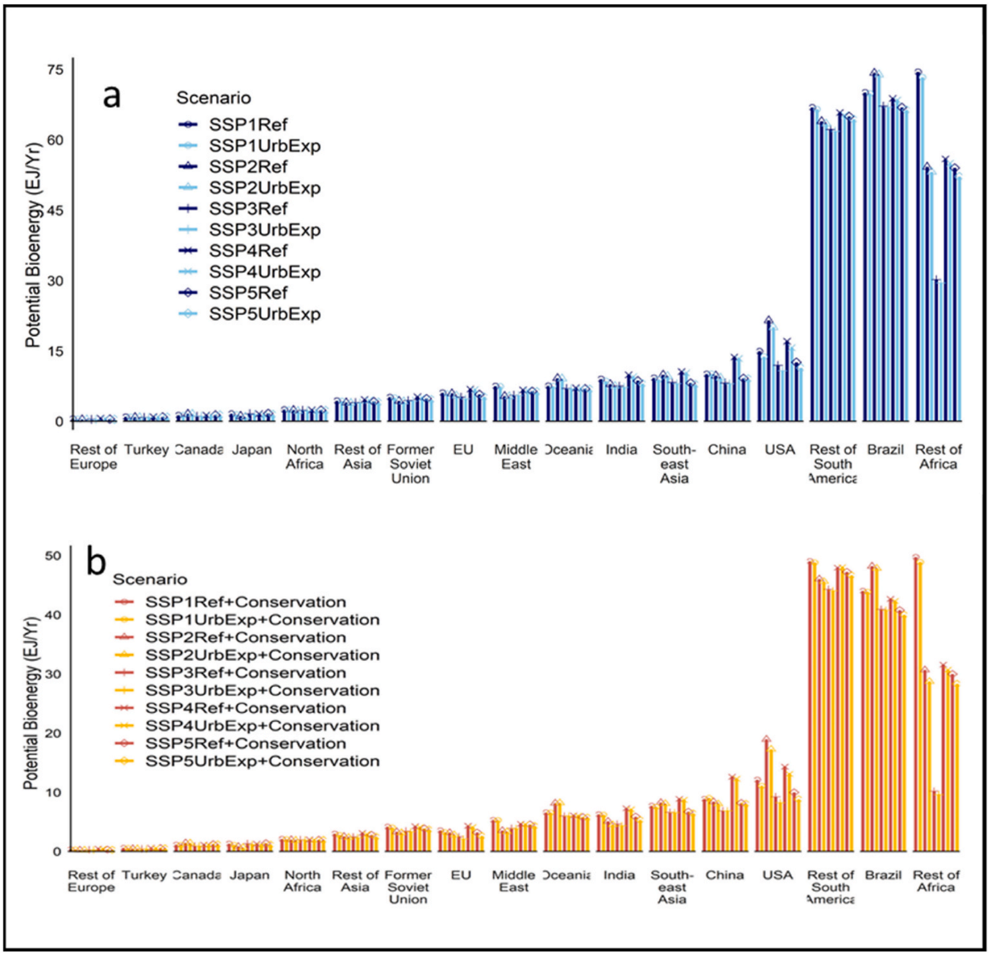

Fig. 5. Regional bioenergy potentials in Reference, urban expansion and conservation scenarios across SSPs. **Panel a.** regional bioenergy potentials in reference and urban expansion scenarios without conservation. **panel b**. regional bioenergy potentials under conservation. Reddish and bluish colors indicate with and without conservation scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Urban expansion affects bioenergy potential more significantly in some regions than others

In the analysis, scenarios were used to link urban expansion and ecosystem conservation with bioenergy reduction. Urban area expansion caused declines in potential bioenergy crop areas and consequent declines in potential bioenergy supply. Bioenergy potential declines were consistently greater in future years due to the increased urban expansion with time. The greater the urban expansion, the greater the declines in bioenergy potentials (Fig. 4). However, these bioenergy potential reductions by urban area expansion were only fractions of total potential; and may only cause concern in particular scenarios and regions. This can be explained by the small proportion of urban area globally and in most regions. Built-up area makes up about 1% of Earth's surface and projections suggest that even the greatest increase by mid-century may not change this fraction very much (Fig. 1). Even in the most developed and rapidly developing regions, projected percentages of urban area to total area are still low[19; see Fig. 3]. Future urban expansion has been projected to be mostly non-residential and thus limited in expanse. Despite the limited expansion, some regions and scenarios attracted our attention. Pursuing a fossil-fueled urban area expansion pathway (SSP5UrbExp) in the rest of Europe for example, would reduce biopotential by 0.08 EJ yr-1. This loss is considerable, given the total biopotential in the region, because it translates to about 17% reduction. The SSP2UrbExp pathway in Japan would translate to 18% reduction in bioenergy potential. The high rates of loss of bioenergy in some regions due to urban area expansion reflect the impact of "local" decisions in land-use management [43]. The expansion style of each region, even though broadly attributed to population and economy, also follows policies of a region that may not always be captured in global modeling studies.

4.2. Population growth, GDP and environmental consciousness affect bioenergy potential

Across both reference and urban expansion SSPs, global bioenergy potentials were highest under the sustainability scenario (SSP1Ref and SSP1UrbExp) and lowest under an urban expansion scenario marked by inequality (SSP3Ref and SSP3UrbExp) (Fig. 4). These estimates are consistent with narratives of SSPs [26]. The SSP5Ref and SSP5UrbExp scenarios had the second-lowest bioenergy potential. While SSP1 and 5 are both assumed to have high income growth, their urbanization levels differ; with SSP5 having much higher levels across regions and globally. Since GDP was one of the input parameters employed in urban area projections [25], this difference in urban expansion is partly due to projected high GDP in SSP5 [51,52] and partly due to high concern for the environment in SSP1. The choice of development pathway therefore affects the amount of bioenergy that can be obtained. The high reduction of potential biomass supply under SSP5 urban expansion (SSP5UrbExp) relative to reference (SSP5Ref) presents a challenge, given the projected high demand for biomass under this scenario [53]. Under SSP2UrbExp in 2050, the rate of reduction relative to reference (SSP2Ref) is 1.6 times

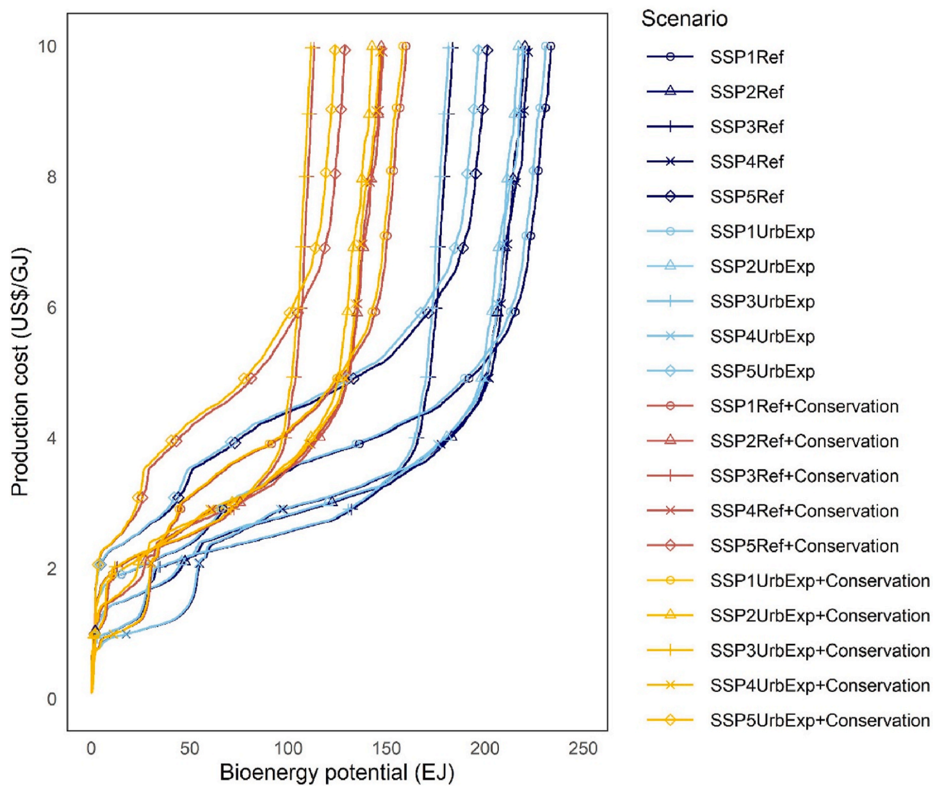

Fig. 6. Global bioenergy supply curve across reference, urban expansion and conservation scenarios. Reddish and bluish colors indicate with and without conservation scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that under SSP1UrbExp. SSP1 is projected to have lower population growth and spatial concentration of urban areas [54], thus more land available for biomass production. The lower rate of urban expansion (Fig. 1) explains the rate of potential bioenergy reduction, which was observed to be relatively stable throughout the century. This implies that whenever possible, urban expansion should be even more limited, encouraging vertical rather than horizontal growth styles. Such change would require better urban planning and zoning [11] policies, especially in the middle-income but rapidly urbanizing regions.

4.3. Yield and cost of production are important factors but availability of land is key

Potential bioenergy estimates in this study are large compared to current total bioenergy consumption. Even under the SSP5 scenario with projected high urban expansion, the estimated 252 EJ yr-1 is 164% of the median projections for bioenergy use in scenarios achieving a 1.5 °C target [35]. Bioenergy potentials strongly followed the amount of bioenergy cropland area available, making potential bioenergy cropland a strong determinant of bioenergy potential. Countries that had slightly larger differences in bioenergy crop area between SSP2 and 5 such as the US, former Soviet Union, China and Brazil showed larger differences in bioenergy potential. Yield also emerged as a strong factor as discussed elsewhere [55]. These results were as expected because technical bioenergy potentials were calculated by multiplying the land area deemed available for bioenergy crops (Table 2) by the yield per unit area and year [40]. Whereas higher yields reduced the amount of land needed for production, higher prices stagnated bioenergy potential growth (Fig. 6). The prices for bioenergy would decrease if more land were available for production as in the SSP1 pathway. In SSP5, higher demand for biomass [53] triggered price increases, showing that the demand for energy across scenarios has a part to play in bioenergy deployment [56].

4.4. Regional analyses beg for common but differentiated governance

Concerning the regions, the estimated supply potential in the EU was quite less compared to actual consumption of bioenergy in its constituent countries [57], suggesting the importance of complimenting energy crops with other sources of biomass in this region. The projections for future demand of bioenergy in EU range between 5 and 19 EJ yr-1 in 2050 [57], which means that our estimates can meet the lower demand. Past analyses have shown that a mix of indigenous biomass resources and energy crops will be needed to sustainably supply a significant portion of UK's energy demand by 2050 [58]. The absolute bioenergy potential results for India showed that impact of urban expansion on bioenergy in one scenario can equal impact of pursuing an alternative socio-economic development pathway (Fig. 5, SSP2UrbExp and SSP3Ref). In the rest of Africa, a sustainability-focused (SSP1) development pathway seems inevitable, if the region wishes to remain the dominant potential bioenergy supplier. Since most of the region is still under-developed, this presents an opportunity and challenge to take up more sustainable urban area expansion. The muted difference in magnitude of bioenergy potential between reference SSP 2 and 5 scenarios in the rest of Africa is due to relatively similar amounts of potential bioenergy crop area (Fig. 3). The impact of projected high population growth in the region was reflected in SSP3 which yielded very low potential bioenergy, representing only 41% of that achieved under SSP1 and 56% of that under the other 3 SSPs. The future SSP1 trends in Japan suggest relaxed population decline and high fertility rates [59], possibly affecting land available for biomass production. Even though high fertility rates are also forecast under SSP5, concentration in cities and technological development will lead to a decline in traditional agriculture and forestry, easing up more land. These findings support the call for "common but differentiated" governance highlighted at the 2021 IEA conference [60].

4.5. Conservation limits bioenergy potential and depending on the region, can either ameliorate or aggravate the impact of urban expansion

Observed trends under conservation have the implication that the scale of bioenergy that both provides net climate benefits and can be sustainably produced is more limited [61] than when conservation is not considered. To put it in context, the 102 EJ average loss observed equals the IEA's estimate for a Net Zero scenario in 2050, about 20% of total world energy supply. It therefore appears that bioenergy production is in direct competition with other land uses [6] including conservation [62], and therefore achieving an ecologically sustainable potential [40] is going to require integrated strategies including land-use zoning [11]. Studies in other regions show a high capacity of biomass to meet significant energy demand even in scenarios where conservation is prioritized [58]. In the urban expansion scenarios, conservation led to the reduction of the rate of loss of bioenergy across scenarios for most regions. For other regions however, the impact of urban expansion on bioenergy potential was aggravated. This finding points to the need to carefully evaluate the spatial relationship between urban areas and protected areas, to avoid undesirable outcomes. Jointly considering bioenergy and ecosystem conservation policies would help to meet the challenge of mitigating both climate change and biodiversity loss [63].

5. Conclusion

This study investigated the effects of urban expansion on global bioenergy potential across SSPs for the year 2050 using the AIM/PLUM model. Results revealed to what extent a decline in bioenergy supply is attributable to expanded fraction of urban area. By mid-century, decreasing bioenergy can be expected under urban expansion, at differential potentials across SSPs. It turned out that the previous model slightly overestimated potential biomass by slightly extended potential bioenergy crop area. By incorporating urban expansion, this study has shown that global and regional estimates of biomass can be improved. In the current model, outputs showed that regardless of the development pathway the world takes, urban expansion will cause a decline in bioenergy potential of at least 4 EJ yr-1 in 2050. This is equivalent to a third of Canada's or Brazil's total energy consumption, according to 2019 estimates. Nevertheless, if urban area expansion is kept at low levels similar to SSP1 projections, then bioenergy reduction rate is not as large as other SSPs. While the global estimates unchanged greatly, some regions showed relatively larger decreases in potential bioenergy when urbanization was considered. Overtime, regional bioenergy potentials were likely to be decoupled from global trends as regional processes, land-use decisions and yields counteract scenarios. Even though regional trends might differ from global trends with respect to development pathways, both spatial levels show a clear pattern of decline of bioenergy potential with increasing urban area.

For sustained biomass supply, overall policies that differentiate socio-economic scenarios as well as policies that seek to protect land at the global level should be of much more interest than the magnitude of change in urban land-use. However, although bioenergy declines due to urban expansion appear small, there is high certainty that they will happen, since urban area expansion cannot be completely halted. It may therefore be worthwhile to explore ways to recover the lost potential, especially in regions that already have low potentials and are classified among highest Greenhouse gas emitters. Vertical development is one strategy that can limit land loss to urban expansion and contribute to achieving the second target of SDG 13.Our findings reiterate the need to maintain long-term monitoring of regional systems. There needs to be greater focus on regional SSP-based trends along with their strengths and weaknesses, as updated datasets become available. The potential conflict between bioenergy supply and food production in some scenarios can impede the achievement of SDG targets; making it necessary for regions to carefully consider their energy policies within the context of the previous state of the land and their development pathways. Innovations such as co-productive farming systems can allow for the production of both food and energy crops, thus limiting the trade-off. Governance strategies can help to ensure the adoption of such innovations. While supply-side issues of production are important, equally important are issues of diet change, which can lead to co-evolution of land availability for biomass production, but these were not yet considered in this study.

In terms of development pathways, if profit-maximization is desirable, either SSP1 or SSP2 are best placed to yield the highest biopotential at a range of costs below 10USD/GJ. For production-maximization, again SSPs 1 and 2 appear most desirable as they have larger available land at a range of yield levels. To achieve an environmental-friendly outcome, each region must keenly interrogate its development priorities; but in general, SSP1 emerges as the bioenergy-efficient urbanization scenario. SSP3 is clearly not desirable especially at the global level and for some of the largest potential bioenergy suppliers, as it yields very low bioenergy potential. The SSP5 pathway may not be desirable even in regions where it yields the highest bioenergy potential, as it has been shown to have strong reduction potential across urban expansion scenarios. In terms of development, the challenges to bioenergy production mainly differ in terms of ratio of available land, price of production and yield estimates. Hence increased urban area under SSP5 reduces ratio of land available for the other land uses and leads to the lowest bioenergy potential. According to the SSP narratives, SSP5 scenario also neglects environmental concerns and is therefore a double-edged sword that gives little (in terms of bioenergy supply) and pollutes more (through excessive use of fossil fuels). But this is also the pathway that leads to the highest GDP and relatively low population rates, hence there is a chance to leverage these points to balance land utilization, as was exemplified in some regions. The chances for overlap between pathways should therefore be sought as much as possible.

In summary, urbanization projections in the SSPs and conservation considerations can serve as an important reference for the analysis of policy options for bioenergy supply. Therefore, there is need to tie energy policies with conservation policies to meet both the goals of mitigating climate change and biodiversity loss.

This study, though comprehensive within the limits of the model, acknowledges some caveats and future potential research areas. First, AIM/PLUM does not account for cropland change effects on biodiversity, therefore the current result is only limited to conservation. Second, there is room to improve biomass estimates by incorporating other biomass crops. Additionally, factors such as higher yield potential to compensate for loss of land area were not incorporated in our model run. Third, this study assumed no climate change, therefore, the potential impacts of anticipated climate change on estimated bioenergy potentials and their differential impacts across scenarios are still unknown.

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Appendix A

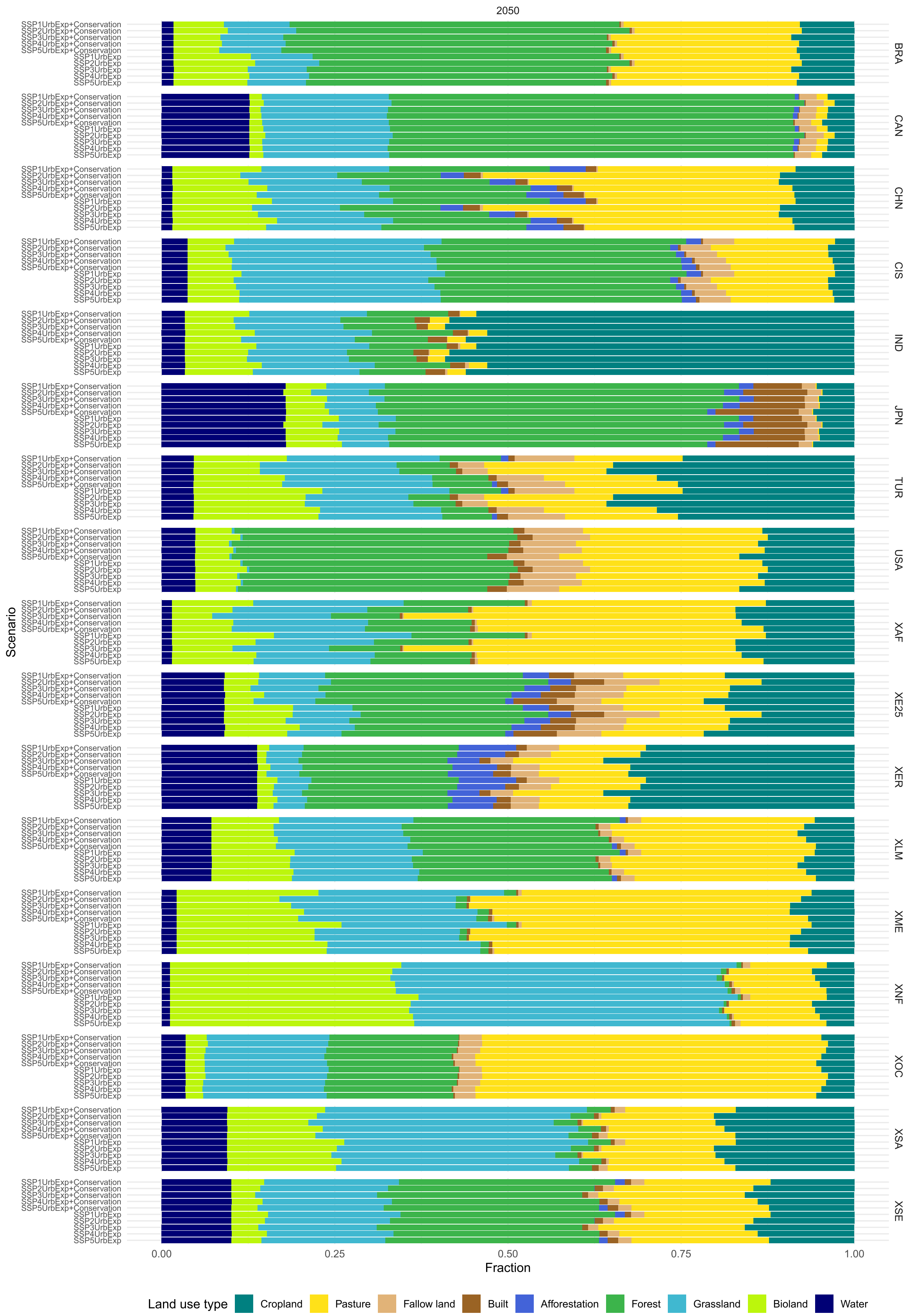

Fig. A1. Land type distribution in 2050 across SSPs under urban expansion and conservation scenarios.

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