## Supporting information

*Table SI: Definition of the 11 regions used in this study.*

| Region name                          | Acronym | Country list                                                                                                                                 |
|--------------------------------------|---------|---------------------------------------------------------------------------------------------------------------------------------------------|
| North America                        | NAM     | Canada, Guam, Puerto Rico, United States of America, Virgin Islands                                                                         |
| Western Europe                       | WEU     | Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom |
| Pacific OECD                          | PAO     | Australia, Japan, New Zealand                                                                                                               |
| Central and Eastern Europe           | EEU     | Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia |
| Former Soviet Union                  | FSU     | Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan |
| Centrally Planned Asia and China     | CPA     | Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam                                                              |
| South Asia                           | SAS     | Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka                                                                 |
| Other Pacific Asia                   | PAS     | American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa |
| Middle East and North Africa         | MEA     | Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen |
| Latin America and the Caribbean      | LAC     | Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela |
| Sub-Saharan Africa                   | AFR     | Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe |

Source: Global Energy Assessment, IIASA
Methods of three recent studies on global energy crop potentials

The WBGU assessment

The WBGU assessment [1] of the global potential of energy crops involved two main components: (1) The simulation of potential biomass yields at dedicated plantations of lignocellulosic energy crops with or without irrigation and (2) a scenario-based evaluation of future land availability for biomass cultivation assuming a set of sustainability guidelines (Figure S1).

![Figure S1. The WBGU approach used to calculate global energy potentials from dedicated bio-energy crops.](image)

Biomass yields of energy crops were simulated with LPJmL, an established global model of the terrestrial land surface representing both natural ecosystems and managed agricultural lands [2,3]. The model includes generic representations of woody crops grown as short rotation coppice and highly productive C4 grasses that are likely candidates for modern biomass plantations. LPJmL simulations of future rain-fed and irrigated yield potentials were driven by 12 different climate scenarios calculated for the Fourth Assessment Report of the IPCC [4].

Following the WBGU’s guardrail principle that defines damage limits to the effects of human activities in order to avoid catastrophic environmental and social consequences, a set of sustainability constraints was defined to estimate available land resources for dedicated biomass plantations. Land currently used for the cultivation of food crops was defined as being unavailable for energy crops in all scenarios, while an additional land requirement of 1.2 million km² (+8%) for food production was assumed in the more restrictive scenarios, based on FAO scenarios [5]. Adopting the approach of Brooks et al. [6], different biodiversity and wilderness indicators were combined to locate the most valuable ecosystems and exclude them from energy crop cultivation. Forests, wetlands and other areas where large amounts of greenhouse gas emissions would result from the conversion to biomass plantations were also excluded. Compared to the influence of assumptions on future nature conservation and agricultural land expansion due to rising food demand, scenarios of irrigation and climate change had only a minor influence on land availability.

According to these analyses, dedicated biomass plantations may occupy between 2.4 and 5.2 million km² in 2050 and could produce between a gross amount of bio-energy between 34 and 120 EJ/yr.
The Erb et al. study

Erb et al. [7] calculate the dependency of the global energy crop potential on possible future changes in diets, agricultural technology and cropland area in 2050. The study is based on a global database for the year 2000 [8,9,10] that integrates global land-use and socioeconomic data with NPP data across a range of spatial scales, from the grid level (5 min resolution, ~10x10km at the equator) to the country level (~160 countries). These databases fulfill multiple consistency criteria across scales and domains: Biomass flows are traced from the NPP of each land-use class to national-level data on primary and final biomass consumption. Empirical data were used to derive factors and multipliers that match the demand for final products of biomass (food, fibres) with gross agricultural production and land use for eleven world regions (http://www.uni-klu.ac.at/socec/downloads/WP116_WEB.pdf).

A biophysical biomass-balance model (Figure S2) was used to assess the feasibility of scenarios by determining whether crop production and roughage supply in 2050 was sufficient to match food demand. Each scenario was characterized by a set of assumptions on future diets (4 variants), livestock feeding efficiencies (three variants), cropland yields (3 variants), and cropland area change (2 variants). Food demand was calculated based on the UN medium population forecast [11] combined with assumptions on different calorie counts and varying proportions of animal products, ranging from extrapolations of current diet patterns in Europe and the US to an assumed global average caloric intake at the level of the year 2000 and an average share of animal proteins of 20%. Livestock feed efficiencies were based on an extrapolation of data derived from FAO statistics for 1961-2000 [12] to 2050, using different assumptions on livestock rearing conditions. Baseline assumptions on yields and cropland expansion are derived from FAO projections [5,13], with two modulations of yields and an additional assumption on cropland expansion that assumed a doubling of the increase in cropland areas compared to the FAO 2050 projection [13].

![Figure S2. The biomass-balance model used in the Erb et al. (2009) study [7].](image)

The following assumptions were made (see [7] for details):

- Diets: The most modest diet variant assumed that calorie supply would remain roughly at the level of the year 2000 (2 800 kcal/cap/day) and 20% of calories would be derived from animal products. The richest diet variant assumed a global conversion towards US and European diet patterns, without fully reaching them until 2050. In that variant, all regions attain food supply levels above 3 000 kcal/cap/day and a substantial increase in the share of animal products. The TREND variant (world average 3 000 kcal/cap/day,
substantial increase in animal product consumption) was similar to FAO projections for 2050 and was the second-richest among the four variants.

- Cropland yields: The highest yield growth variant considered in [7] was based on the FAO 2050 projection [13] which forecasts yield increases of 54% (weighted average of all regions and crops), the lowest assumed a global transition towards organic agriculture in which maximum yields were assumed to be 40% lower than the highest yield levels of conventional cropping systems, but higher than today in many regions. The third variant assumed yields between these two extremes. Additional calculations not reported in [7] were performed, assuming yield growth according to the ‘Global Orchestration’ scenario of the Millennium Ecosystem Assessment [14], i.e. 9% higher yields than those forecast by the FAO for 2050. A comparison of the TREND scenario (FAO yields, TREND diet and livestock conversion efficiency) with a scenario in which everything else would remain the same except yields (+9%) showed that higher yields would raise the energy crop potential from 77 to 90 EJ/yr, i.e. by 13 EJ/yr (+17%).

The model operates at the level of eleven world regions. If gaps occurred in a region between regional supply and demand for animal and/or cropland products, they were assumed to be balanced by trade. Following a ‘food first’ approach, scenarios in which global cropland area demand exceeded global cropland availability were labeled ‘non-feasible’ and not further considered (grazing area potential was not found to be limiting). The model calculated the area available for growing bio-energy crops and the resulting bio-energy crop potential by summing up the area potential on cropland and the area potential on grazing areas. Yields were assumed based on the NPP of these areas, a procedure also used in other studies (e.g., 15,16]). In order to understand the latter, it is necessary to discuss how the potential grazing land area was derived in the underlying land-use dataset [8].

This dataset was derived by calculating the area potentially available as grazing land by subtracting from each pixel’s total area (1) infrastructure and urban areas, (2) cropland areas, (3) forestry areas and (4) unused areas (‘wilderness’). Hence, the potential grazing land area in that dataset includes the total land area that is not either (a) used by humans for any other purpose than grazing or mowing or (b) classified as ‘wilderness’. Forests are either classified as forestry areas (3) or pristine forests, in which case they are included in the ‘wilderness’ category (4). The ‘wilderness’ area (approximately one quarter of the global land surface excluding Greenland and Antarctica) holds little promise for energy crops because most of it is extremely unproductive, the (relatively small) remainder being pristine forest which were excluded due to very long carbon payback times and biodiversity conservation. Potential grazing land according to [8] therefore includes meadows and grazing lands, abandoned farmland, degraded land and all other lands without forests. The map of grazing area extent is complemented by a map discerning four classes of grazing suitability. This map was based on land cover information from the GLC2000 combined with data on potential NPP in each gridcell, assuming a correlation of grazing suitability with productivity and land cover, e.g. high suitability of cultivated and managed areas, medium suitability of grazing land found under tree cover, and low suitability if shrub cover or sparse vegetation was detected by remote sensing. Grazing class 1, the most suitable class for grazing, includes areas identified as managed by humans with an aboveground NPP above 200 gC/m²/yr (for references see [8]). Feed demand of livestock not covered by cropland products was assumed to be met by roughage supply from grazing land.

In order to identify the area that would be available for energy crops, it was assumed that the most suitable grazing areas (Grazing class 1) could be intensified up to levels found in the regions where grazing areas are currently used most intensively. That is, it was assumed that,
given appropriate management, stocking densities on grazing land (or roughage harvest) could be increased which would set free area for energy crops.

The study found that, depending on future diets, yields and livestock feeding efficiencies, 2.3-9.9 million km² of land would be available for energy crops, yielding between 28 and 128 EJ/yr of primary plant material. Compared to the WBGU study, land potentials are mostly higher because only land demand for roughage supply was taken into account as a constraint (e.g., no restrictions for nature conservation were assumed). Yield levels were lower than those estimated by WBGU for two reasons: (1) the study assumed that high-quality land would be first used for food supply and only remaining less productive areas would be available for energy crops, (2) the WBGU explicitly modeled the use of the most efficient plants (short-rotation coppice, C₄ grasses) and also assumed irrigation, while this study assumed only natural productivity levels without irrigation.

**The van Vuuren et al. (2009) study**

Van Vuuren et al. [17] calculated global bio-energy potentials from woody energy crops in 2050 using the IMAGE 2 model. The integrated assessment model IMAGE 2 and the global energy model TIMER have been used earlier to estimate the technical and economic potential of bio-energy [18,19]. The methodology is described in detail elsewhere [18]. Figure S3 gives an overview of the feedbacks considered in the van Vuuren et al. study. First, it is assessed which areas can be used for energy production given the physical-geographical characteristics and other land requirements. To this end, the IMAGE model is used to describe land use in the absence of biomass production.

In addition to the previous work done with the IMAGE 2 model, van Vuuren et al explore how other factors such as land degradation, water scarcity and areas dedicated for biodiversity conservation may influence such estimates. Various overlays are made and with geographical explicit data in a half-degree grid (0.5⁰ x 0.5⁰). Degraded areas were estimated based on the GLASOD database [20], water scarcity data were based on results from the Water Gap model used in the OECD Environmental Outlook [21]. Biodiversity areas were taken from the ‘Sustainability First’ scenario of the UNEP Global Environmental Outlook [22].

![Figure S3. Methodology of the van Vuuren et al. study to calculate global bio-energy potentials [17].](image)

Assuming the land-use scenario of the OECD Environmental Outlook [21] for the year 2050, Van Vuuren et al. calculated an unconstrained bio-energy crop potential of approximately 150
EJ/yr. If establishment of new biodiversity reserves, strongly water scarce areas and strongly degraded areas were excluded, the bio-energy crop potential dropped to approximately 115 EJ/yr. If mildly water-scarce and degraded areas were also excluded, the potential was reduced to 65 EJ/yr. It should be noted that IMAGE calculated much higher biomass yields per unit area and year than the WBGU, based on LPJmL. While biomass yields were 19-60 MJ/m²/yr according to IMAGE, LPJmL calculated yields of 14-23 MJ/m²/yr (see Table 1).

Van Vuuren et al. also calculated global potentials for woody bio-energy crops that would result from additional yield increases of both food and energy crops. If all (food and energy) crops were assumed to grow 12.5% more than assumed in the reference scenario, the global energy-crop potential could reach up to 230 EJ/yr. Another scenario calculation assumed different land-use scenarios derived from the ‘Special Report on Emission Scenarios’ (SRES) report [23]. These calculations demonstrated the strong impact of future land-use change on bio-energy crop potentials and gave a range from 120-300 EJ/yr, with the lowest energy-crop potential in the A2 scenario due to high population growth, low yields and little trade. The highest bio-energy crop potential was found in the B1 scenario with low population growth and rapid growth of yields. These latter calculations did, however, not consider constraints such as biodiversity conservation.
**Strengths and weaknesses of the three studies**

Table S2 summarizes the three studies used to estimate bioenergy crop potentials. It analyzes strengths and weaknesses, suggesting that the studies have complimentary strengths.

Table S2. Summary of modelling strategies, strengths and weaknesses of the three studies.

| Study            | Core modelling strategy                                                                 | Strength                                                                 | Weaknesses                                                                 |
|------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|
| WBGU             | o Dynamic global vegetation model with an explicit representation of energy crops (LPJmL)  | o Modelling of energy plant growth with one of the most advanced mechanistic vegetation models (LPJmL) | o No representation of livestock / feed supply                             |
|                  | o Assumptions on area availability based on external datasets                           | o Considers woody and herbaceous (C4) plants                             | o Simple representation of effects of future changes in diets and agricultural technology on area available for energy crops (constant cropland, +8%) |
|                  |                                                                                         | o Consideration of multiple sustainability criteria                      |                                                                           |
|                  |                                                                                         | o Explicit assessment of the effects of irrigation on energy crop potentials |                                                                           |
| Erb et al.       | o Biomass-balance model based on thermodynamic principles and data for the year 2000  | o Strong and consistent empirical basis for year 2000                    | o No consideration of other area constraints than feed supply              |
|                  | o Assumptions on changes in population, diets, cropland yields, livestock feeding efficiency based on FAO studies and databases | o Extremely simple and transparent model design (mass balance)            | o Simple assumptions on energy crop yields                                 |
|                  |                                                                                         | o Explicit representation of diet changes, changes in agricultural technology (yields, livestock) and cropland area | o Empirical ‘black-box’ model, no process-based mechanistic components, no optimization and limited internal feedbacks |
| Van Vuuren et al.| o Integrated assessment model IMAGE, energy module TIMER (part of IMAGE)               | o Well-established, fully integrated modeling framework                  | o Yield levels of bio-energy crops seem high (see [1,24])                  |
|                  | o Land-use scenarios from OECD and SRES                                                 | o Ability to simulate various feedbacks                                  | o Simple assumptions on land accessibility                                 |
|                  | o Constraints based on GLASOD, UNEP and OECD work                                       | o Explicit analysis of the sensitivity of results to different assumptions on land use |                                                                           |
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