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**ANALYSIS**

# The global technical and economic potential of bioenergy from salt-affected soils†

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This study assesses the extent and location of salt-affected soils worldwide and their current land use and cover as well as the current technical and economic potential of biomass production from forestry plantations on these soils (biosaline forestry). The global extent of salt-affected land amounts to approximately 1.1 Gha, of which 14% is classified as forest, wetlands or (inter)nationally protected areas and is considered unavailable for biomass production because of sustainability concerns. For the remaining salt-affected area, this study finds an average biomass yield of 3.1 oven dry ton ha$^{-1}$ y$^{-1}$ and a global technical potential of 56 EJ y$^{-1}$ (equivalent to 11% of current global primary energy consumption). If agricultural land is also considered unavailable because of sustainability concerns, the technical potential decreases to 42 EJ y$^{-1}$. The global economic potential of biosaline forestry at production costs of 2€ GJ$^{-1}$ or less is calculated to be 21 EJ y$^{-1}$ when including agricultural land and 12 EJ y$^{-1}$ when excluding agricultural land. At production costs of up to 5€ GJ$^{-1}$, the global economic potential increases to 53 EJ y$^{-1}$ when including agricultural land and to 39 EJ y$^{-1}$ when excluding agricultural land. Biosaline forestry may contribute significantly to energy supply in certain regions, *e.g.*, Africa. Biosaline forestry has numerous additional benefits such as the potential to improve soil, generate income from previously low-productive or unproductive land, and soil carbon sequestration. These are important additional reasons for investigating and investing in biosaline forestry.

## Broader context

In recent years the sustainability of the production and use of energy from plant biomass (bioenergy) has become an issue of global concern. Key issues are the direct and indirect effects on land use, biodiversity, food security, and greenhouse gas emissions. The use of degraded or low-productive land for the production of bioenergy is often proposed as a solution to these problems. However, there is little knowledge on the location and extent of degraded land worldwide, the current use and vegetation cover of degraded land, the impact of degradation on yields, or the economics of biomass production on degraded land. Salt-affected land is an important type of degraded land because of its large current global extent, the continued salinization of agricultural land, and the challenges that it poses to agriculture. However, many tree species are less susceptible to soil salinity and sodicity than agricultural crops, and forestry plantations may thus allow the cultivation of salt-affected land that would otherwise remain unused or have low productivity levels. This study therefore assesses the extent and location of salt-affected soils worldwide and their current land use/cover as well as the current technical and economic potential of biomass production from forestry plantations on these soils.

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## 1. Introduction

In recent years the sustainability of the production and use of energy from plant biomass (bioenergy) has become an issue of global concern.[1] Key issues are the direct and indirect effects on biodiversity and on food security as well as the greenhouse gas emissions. The use of degraded or low-productive land for the production of bioenergy is often proposed as a solution to these problems. The use of degraded land, which is largely unsuitable for crop production, can reduce (in)direct competition with food production for higher quality land.[1] The use of degraded land can also increase biodiversity, especially if monoculture and large fields are avoided,[2] and improve the greenhouse gas balance by increasing the soil organic matter content as a result of above- and belowground biomass growth.[3,4] Moreover, the use of previously low-productive areas can contribute to economic growth and create new employment opportunities. However, the use of degraded and low-productive land also has drawbacks that potentially limit its economic attractiveness. Most important are lower yields and higher levels of agricultural inputs such as fertilizers, chemicals, *etc.*, compared to high quality soils.

While previous studies have analyzed bioenergy production from low-productive or degraded land, these studies did not account for either the type and severity of degradation or the impact of degradation on crop yields.[5–8] However, these factors can be crucial for the proper design of energy crop production systems and the performance of these systems. In addition, limited attention has been paid to the present use and vegetation cover of degraded and low-productive land. A more in-depth analysis of biomass production in relation to the type and degree of land degradation and to current use of degraded land would allow a better estimation of the potentials. Nijsen *et al.*[9] made a first attempt at such an analysis for human-induced degradation and found that the potential of woody crops on degraded land not used as forest, cropland, or pastoral land amounts to 30 to 40 EJ $y^{-1}$. However, Nijsen *et al.*[9] do not account for salt-affected soils nor for any natural degradation although human-induced salt-affected soils are estimated to amount to 76 Mha[10] while natural and human-induced salt-affected soils combined are estimated between 400 Mha and 960 Mha,[11–14] depending on the datasets and the classification systems used. In addition, salinization of agricultural land continues to occur mainly as a result of mismanagement of irrigated soils, and the annual rate of new irrigation-induced salinization is estimated at 0.25 to 0.5 Mha globally.[15] Furthermore, salt-affected land poses challenges to conventional agriculture because most agricultural crops are salt-intolerant. Increased salt concentrations impede plant growth by increasing the osmotic pressure of the soil solution, which in turn hampers water extraction by plant roots and thereby growth rates (the osmotic effect) and by increasing the concentrations of chloride and sodium ions in the plant, which leads to toxicities in the plants and thereby to cell injury and growth reduction (the specific ion effect).[16,17] Many tree species are less susceptible to soil salinity and sodicity than agricultural crops, and forestry plantations with these species may thus allow the cultivation of salt-affected land (hereinafter, biosaline forestry) that would otherwise not be used or would have low productivity levels. Examples of such salt-tolerant tree species are *Acacia nilotica*, *Casuarina equisetifolia*, *Prosopis juliflora*, and *Tamarix aphylla*.[18] Wood from salt-affected soils can be used for nearly any application of wood without modifications, although co-firing it with coal to produce electricity or gasifying it for liquid fuel production is limited due to higher salt content in the wood leading to corrosion of the equipment.[19] Two examples are the use of saline land for the production of biomass for the local pulp and paper industry in the Yellow River Delta region in China[20] and the use of sodic soils for fuelwood and charcoal production in the northern Indian state of Haryana.[21]

Given the large global extent of salt-affected soils, the continued salinization of agricultural land, and the difficulties of using these lands for agricultural production, the present study focuses on the potential of bioenergy production from biosaline forestry. The objective of this study is to estimate the current technical and economic potential of woody energy crops cultivated on salt-affected land. This is done by first classifying and mapping the different types of salt-affected land and assessing their current use by applying land use and cover data. Next, a tree growth model is constructed to estimate the yields of different salt-tolerant tree species in salt-affected environments. The results of the first and second steps are then combined to estimate the technical bioenergy potentials from salt-affected land. Finally, the costs of biomass production are calculated and cost–supply curves constructed to evaluate the economic potential of energy crop production on salt-affected soils.

The remainder of this paper is organized as follows. In Section 2, the methodology used in the four abovementioned steps is explained. Section 3 describes the spatial datasets, the tree requirements used for determining the yields, the cost data used in the economic potential analysis, and other input data. The results, including the extent and location of salt-affected soils, the yields, and the technical and economic potential of biomass production from salt-affected soils, are presented in Section 4. Section 5 discusses methodological choices, uncertainties in the data and the results. Section 6 concludes the study with final remarks.

## 2. Methodology

A spatial resolution of 1 arcminute is applied throughout the analyses. All datasets are converted to this resolution.

### 2.1. The extent and location of salt-affected areas

Salt-affected soils are commonly considered to comprise saline, sodic, and saline-sodic soils.[22] *Saline soils* are characterized by the presence of soluble salts in such quantities that they interfere with plant growth.[23] They have a high electrical conductivity of the saturated soil extract (ECe) but a low exchangeable sodium percentage (ESP). *Sodic soils* refer to an excessive amount of sodium on the exchange complex of the soil (high ESP), while the total amount of salts is low (low ECe).[23,24] Sodic soils often have a high pH (above 8.5). *Saline-sodic soils* contain excessive amounts of soluble salts (high ECe) and have enough exchangeable sodium to affect plant growth (high ESP), while the pH is generally below 8.5.[24]

In this study, the severity levels of saline and sodic soils are based on the existing classification system of the US Salinity Laboratory[22] and defined based on ECe and ESP, respectively

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(Table 1). Severity levels of saline-sodic soils are defined here based on a combination of the severity levels of saline soils and sodic soils (Table 1).

Based on this classification, the location of salt-affected land is mapped and the global extent is calculated in a Geographic Information System (ESRI ArcGIS 9.3.1) using the Harmonized World Soil Database (HWSD).[25] The HWSD has some shortcomings related to compiling a global dataset from a range of sources and to an uneven distribution of soil profile analysis (for a discussion of the shortcomings see FAO, IIASA, ISRIC, ISS-CSA and JRC[25]). Nevertheless, it is the most comprehensive, detailed, and updated global soil database currently available. The HWSD includes soil characteristics for topsoils (0–30 cm) and subsoils (30–100 cm). Average soil salinity and sodicity are calculated by applying weighting factors of 60% for topsoils and 40% for subsoils. These factors are based on the distribution of tree roots in the soil.[26] The HWSD mapping units are divided in up to nine soil units. If not all soil units are salt-affected, only the extent of the salt-affected soil units is considered by multiplying the mapping unit's area by the percentage share of the soil unit.

## 2.2. Yields of forestry plantations on salt-affected soils

The yields of biosaline forestry are determined separately for (sub)tropical and temperate regions. For (sub)tropical climates, the yield estimation model for salt-affected environments in (sub) tropical regions of Vashev *et al.*[26] is used (Section 2.2.1). For temperate climates, a similar method based on a modified version of the Crop and Grass Production Model of Leemans and van den Born[27] is applied (Section 2.2.2).

**2.2.1. Yields of forestry plantations on salt-affected soils in (sub)tropical climates.** The yields of forestry plantations on salt-affected soils in (sub)tropical regions are calculated using a modified version of the yield estimation model of Vashev *et al.*,[26] which is based on Sys *et al.*'s[28] refined version of the FAO[29] Framework for Land Evaluation and matches climate, soil, and terrain requirements of salt-tolerant tree species (hereinafter, tree requirements) suitable for (sub)tropical regions with the characteristics of the land under consideration. Vashev *et al.*[26] derive the tree requirements for tropical, salt-tolerant tree species from (1) the literature, (2) regression analyses using a database of measurements from pot trials and case studies of biomass production on salt-affected soils, and (3) expert judgment.

The following (groups of) land characteristics are distinguished with respect to soil and terrain:

- *topography* (slope gradient),
- *wetness* (internal drainage class),
- *physical soil characteristics* (gravel content, drainage class, soil texture class, gypsum, calcium carbonate content),
- *chemical soil characteristics* (cation exchange capacity of the clay fraction, base saturation, total exchangeable bases, organic carbon, pH ($H_2O$)), and
- degree of *salinity–alkalinity* (electrical conductivity, exchangeable sodium percentage).

Vashev *et al.*[26] include three additional land characteristics (flooding, soil depth, and depth of groundwater) for which global data are unavailable or insufficient to be able to include them in the global analysis (see Section 5 for a discussion). In addition to land characteristics, the following climatic characteristics are taken into account:

- *rainfall* (annual precipitation, length of dry season),
- *temperature* (mean maximum temperature of the warmest month, mean minimum temperature of the coldest month, mean annual temperature), and
- *radiation* (fraction of sunshine hours).

Depending on the tree-specific requirements, ratings between 0 (unsuitable) and 100 (very suitable) are defined, indicating the level of limitation for the growth of the tree species under the given climate and land characteristics. A climate index and a soil and terrain index are then calculated based on the theory that the scarcest resource is the limiting factor for plant growth. This is done by selecting the ratings of the most limiting factor within each group of land and climate characteristics and by multiplying them (eqn (1)).[28]

$$I_{[\mathrm{tropS,tropC}]} = A \times (B/100) \times (C/100) \times (D/100) \ldots \qquad (1)$$

where $I_{\mathrm{tropS}}$ [unitless]—soil and terrain index; $I_{\mathrm{tropC}}$ [unitless]—climate index; $A$, $B$, $C$, $D$, …—rating of the most limiting factor within each group of land characteristics (topography, wetness, physical soil characteristics, chemical soil characteristics and salinity–alkalinity) and climatic characteristics (rainfall, temperature and radiation).

The climate index and the soil and terrain index indicate the impact of climate, and soil and terrain separately. To calculate a land index that combines climate, soil, and terrain characteristics, the climate index is first recalculated into a climate rating ($R_C$, unitless) following eqn (2) (based on Sys *et al.*[28]).

**Table 1** Characterization of different types of salt-affected land and their severity levels (average for 1 m soil depth)

| Type of salt-affected land | Indicator | Severity level<br>Slight | Moderate | High | Extreme |
|---|---|---|---|---|---|
| Sodic | ESP (%) | 15–20 | 20–30 | 30–40 | >40 |
| | ECe/dS m$^{-1}$ | <4 | <4 | <4 | <4 |
| Saline | ECe/dS m$^{-1}$ | 2–4 | 4–8 | 8–16 | >16 |
| | ESP (%) | <15 | <15 | <15 | <15 |
| Saline-sodic | ESP (%), ECe/dS m$^{-1}$ | 15–20, 4–8 | 15–20, 8–25;<br>20–30, 4–16;<br>30–40, 4–8 | 15–20, >25;<br>20–30, 16–25;<br>30–40, 8–16;<br>40–50, 4–8 | 20–30, >25;<br>30–40, >16;<br>40–50, >8;<br>>50, >4 |

$$R_C = \begin{cases} I_{\mathrm{tropC}} \times 1.60, \text{when } 0 \le I_{\mathrm{tropC}} \le 25.0 \\ I_{\mathrm{tropC}} \times 0.94 + 16.67, \text{ when } 25.0 < I_{\mathrm{tropC}} \le 92.5 \\ I_{\mathrm{tropC}}, \text{ when } 92.5 < I_{\mathrm{tropC}} \le 100.0 \end{cases} \quad (2)$$

The climate rating is then multiplied by the soil and terrain index to determine a land index ($\mathrm{LI}_{\mathrm{trop}}$, unitless) (eqn (3)), which represents the suitability of the land for the given tree species and is relative to the constraint-free yield.

$$\mathrm{LI}_{\mathrm{trop}} = R_C \times (I_{\mathrm{tropS}}/100) \quad (3)$$

Values for the $\mathrm{LI}_{\mathrm{trop}}$ range between 0 (not suitable) and 100 (very suitable). To estimate the actual yield ($Y_{\mathrm{trop}}$, oven dry ton (odt) $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$), the $\mathrm{LI}_{\mathrm{trop}}$ is multiplied with the constraint-free yield ($Y_{\max}$, odt $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$):

$$Y_{\mathrm{trop}} = Y_{\max} \times (\mathrm{LI}_{\mathrm{trop}}/100) \quad (4)$$

The constraint-free yield of the (sub)tropical tree species is approximated by applying the maximum yields recorded in the literature. A management factor that accounts for differences in theoretical and actual yields is not applied in the tropical model because the yields used in the study refer either to actual yields obtained at plantations (*Acacia nilotica*[30] and *Prosopis juliflora*[31]) or to a calculated potential yield that accounts for the harvest index (*Eucalyptus camaldulensis*[32]). Results are generated for three salt-tolerant species, which have shown promising yields in pot trials, field experiments, and the literature, and for which sufficient data are available.[26] These species are *Eucalyptus camaldulensis*, *Acacia nilotica*, and *Prosopis juliflora*. For the potential analysis, the yield in each grid cell is defined by the species with the highest yield.

**2.2.2. Yields of forestry plantations on salt-affected soils in temperate climates.** The yields of forestry plantations on salt-affected soils in temperate climates ($Y_{\mathrm{temp}}$) are estimated using a modified version of the Crop and Grass Production Model (CGPM) of the Integrated Model to Assess the Global Environment (IMAGE).[27,33] In the CGPM, climate-constraint yields ($Y_{\mathrm{clim}}$) are calculated and multiplied by a soil reduction factor that accounts for soil and terrain limitations to crop production. This soil reduction factor (hereinafter referred to as the soil index, $I_{\mathrm{tempS}}$, in line with the terminology used in the (sub) tropical model) is determined as follows:

$$I_{\mathrm{tempS}} = 0.005 \times R_g \times (R_{\mathrm{nr}} + R_{\mathrm{sy}} + R_{\mathrm{ro}} - R_g) \quad (5)$$

where $I_{\mathrm{tempS}}$ [unitless]—soil index; $R_{\mathrm{nr,sy,ro}}$ [unitless]—rating of the most limiting factor within each of the three soil quality indicators: *nutrient retention and availability* ($R_{\mathrm{nr}}$; fertility), *level of salinity*, *alkalinity and toxicity* ($R_{\mathrm{sy}}$; salinity, pH, sodicity) and *rooting conditions* for the plants ($R_{\mathrm{ro}}$; rooting depth, drainage); and $R_g$ [unitless]—minimum of $R_{\mathrm{nr}}$, $R_{\mathrm{sy}}$, and $R_{\mathrm{ro}}$. All ratings range between 0 (unsuitable) and 100 (very suitable).

In order to better account for the salt-tolerance of some tree species, the first modification applied to the CGPM by the present study is the way the ratings for $I_{\mathrm{tempS}}$ are calculated. In the original model, the ratings for each crop type are defined per soil class. In the present study this is done only for the rating of nutrient retention and availability and the rating of rooting depth. The other ratings are defined based on the average tree requirements of the three species used in the (sub)tropical model assuming that the soil and terrain requirements of temperate tree species are similar to those of tropical species. This assumption is made because tree requirements for salt-tolerant, temperate species do not yet exist. However, salt-affectedness is the main parameter in this study, and the literature on the salt-tolerance of temperate tree species, including those applied in the IMAGE model (*e.g.*, poplar and willow species), indicates that various temperate tree species are also salt-tolerant.[34–36]

The biomass yield for salt-affected soils in temperate regions ($Y_{\mathrm{temp}}$) is then calculated by multiplying the climate-constraint yield from the CGPM by the soil index and a management factor (eqn (6)). A management factor of 0.7 is applied to account for differences in theoretically feasible and actual yields.[37]

$$Y_{\mathrm{temp}} = Y_{\mathrm{clim}} \times (I_{\mathrm{tempS}}/100) \times \mathrm{MF} \quad (6)$$

where $Y_{\mathrm{clim}}$ [odt $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$]—climate constraint yield; $I_{\mathrm{tempS}}$ [unitless]—soil index (eqn (5)); and MF [unitless]—management factor.

A second modification to the CGPM is made with respect to the soil database applied for calculating the soil index. The HWSD[25] is used because it is more updated and detailed than the DSMW[38] used in the original model.

## 2.3. Technical potential of biomass production on salt-affected soils

The technical potential of biomass production on salt-affected soils is determined per grid cell by multiplying the available salt-affected area by the yield corresponding to the climate and soil characteristics of the grid cell. Salt-affected land is assumed to be available if it is not classified as forest, wetland, unsuitable areas (*e.g.*, urban areas), or (inter)nationally protected areas. Agricultural land is not excluded in the potential assessment because conversion to a forestry plantation can reduce the risk of further degradation of the land and may even help improve the soil.[39–42] However, the use of agricultural salt-affected land for biomass production may not be desirable for various reasons, most importantly food insecurity and (in)direct land use change. Therefore, the fraction of the technical potential originating from agricultural land is distinguished.

## 2.4. Economic potential of biomass production on salt-affected soils

The economic potential is in this study defined as the part of the technical potential that can be produced at a certain (attractive) cost level. Due to the large number of biomass applications and conversion technologies, it is not possible to determine the competitiveness for all combinations of applications and conversion technologies. Instead, the focus is on the cost of the biomass production. A figure of 2€ $\mathrm{GJ}^{-1}$ or below is assumed to be an attractive range for the costs of biomass feedstock production because at this level large scale production of second generation liquid biofuels is expected to become competitive with conventional gasoline, assuming that technological developments will be stimulated.[43] Co-firing biomass with coal for electricity production is also competitive at this level given that the

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current price of coal is 2.3€ GJ$^{-1}$.[44] A range of 2 to 5€ GJ$^{-1}$ can still be considered attractive for certain applications, but attractiveness depends heavily on the price of oil if the biomass is intended for energy and chemical purposes. More detailed and site-specific analysis will be required on whether the applications of biomass from salt-affected soils are indeed economically feasible.

The economic potential is determined by constructing cost–supply curves for biomass production from biosaline forestry. These curves are made by ranking the technical potential as a function of production costs per grid cell. The farm-gate production costs (in US$ GJ$^{-1}$) are calculated by applying discounted values for costs and biomass yields because costs and benefits from biomass production are distributed unequally over time.[45,46] Converting physical units (*i.e.*, the yield) into annuities may be uncommon, but the concept is essentially the same as converting costs into annuities because physical units also represent monetary values. The production costs are determined as follows:

$$P_{\text{cost}} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \times \text{EC}^{-1} \times \left( \sum_{t=0}^{n} \frac{X_t}{(1+r)^t} \right)^{-1} \qquad (7)$$

where $P_{\text{cost}}$ [€ GJ$^{-1}$]—costs of production, $C_t$ [€ ha$^{-1}$]—costs of the forestry plantation in year $t$, $X_t$ [odt ha$^{-1}$]—yield of wood in year $t$, EC [GJ odt$^{-1}$]—energy content of woody biomass, $r$ [%]—discount rate, and $n$ [y]—lifetime of the project.

The range of forestry systems suitable for salt-affected soils varies with respect to factors such as the management system (fertilizer application rate, use of irrigation, level of mechanization), the tree species, the use of intercropping, and the planting density. The economic attractiveness of each system depends primarily on the price of biomass, land, labor, capital and other inputs; the availability of infrastructure; and the costs of transportation. A detailed evaluation to determine the optimal systems in each grid cell is not possible on a global scale due to a lack of data. Instead, a generalized forestry system that includes all elements and cost items of a typical forestry plantation is defined. The generalized production system assumes two rotation periods of ten years each. The establishment phase involves soil preparation, planting of trees (at a tree density of approximately 800 trees per hectare), weeding, pruning, and fertilizing. Irrigation is considered only during the establishment phase to improve tree survival and not as part of the maintenance of the plantation.

The maintenance of forestry plantations requires weeding, fertilizing, and pruning. Weeding is assumed to be required only in the first three years after establishment and in the first year after the harvest. The nitrogen, phosphorus, and potassium fertilizer requirements are determined by means of a nutrient balance methodology, which assumes that the nutrients taken up by the crop during its growth must be replenished by fertilizers in order to maintain the soil's nutrient composition.[47] While this is a simplification of the actual practice, it enables a fair comparison of fertilizer requirements in different regions with different productivities.

Harvesting and in-field transportation can be a manual labor-based system (using only chainsaws and manpower), a fully mechanized system (using large, self propelled harvesters, forwarders, and tractors), or one of various intermediate systems. The choice of the system depends primarily on the price of labor and machinery. Because the type of system applied affects the costs of harvesting and transportation of the biomass to the edge of the field, this study defines three harvest systems, namely, one manual, one fully mechanized, and one intermediate system, to account for the many different possible levels of mechanization. In this study, the definition of the three systems is based on data on labor input and machinery costs from the literature (see Table 5). A constant price of capital is assumed across all countries meaning that the price of agricultural labor determines which harvesting system is used in each country.

Another important factor in the production cost of biomass is the land rent. The rent of degraded land depends on many factors such as the severity of the degradation, the distance to cities, and available infrastructure. Because only few data points are available, regional costs of land rent are taken from Hoogwijk *et al.*[48] and corrected for the lower value of salt-affected land compared to high quality agricultural land. The correction factor is based on the ratio of average yields of salt-affected soils and average forestry plantation yields in the global potential study of Hoogwijk *et al.*[48] Although this is a rough approach, it provides an initial estimate that can be used in this study.

## 3. Input data

Although the scope of this assessment is global, results for 17 world regions[49] are generated in order to show the impact of regional differences on soil and climate (and thereby in yield) and on the price of land, labor, and inputs. Regional or country specific data are included whenever available.

### 3.1. Spatial datasets

The extent and location of salt-affected soils worldwide are determined with the HWSD.[25] Current land use and land cover of salt-affected land is assessed by applying the Global Land Cover Database for 2000.[50] Nationally and internationally protected areas are accounted for by the World Database on Protected Areas.[51]

All soil parameters used in the yield model are extracted from the HWSD.[25] Slopes are mapped with the median slope gradient map of IIASA and FAO.[52] All climate parameters, except the *length of dry season*, are extracted from the CRU TS 2.1 dataset,[53] applying the average between 1981 and 2002. The parameter *length of dry season* is determined using monthly precipitation data from the CRU TS 2.1 dataset[53] and monthly reference evapotranspiration from FAO.[54] (Sub)tropical and temperate regions are distinguished using the Thermal Climate Zones Map from FAO.[55]

### 3.2. Yields

The tree requirements applied in determining the soil and terrain index and the climate index are presented in Tables 2 and 3, respectively. Constraint-free yields for the harvested biomass of the (sub)tropical tree species ($Y_{\text{max}}$) are estimated at 41 odt ha$^{-1}$ y$^{-1}$ for *Acacia nilotica*,[30] 38 odt ha$^{-1}$ y$^{-1}$ for *Eucalyptus camaldulensis*,[32] and 39 odt ha$^{-1}$ y$^{-1}$ for *Prosopis juliflora*.[31] In the

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**Table 2** Soil and terrain requirements for *Eucalyptus camaldulensis*, *Acacia nilotica* and *Prosopis juliflora*[26]

| | | Rating | | | | | |
|---|---|---|---|---|---|---|---|
| Land Characteristics | Species[a] | 100 | 90 | 72.5 | 50 | 32.5 | 12.5 |
| *Topography* | | | | | | | |
| Slope (%) | All species | 0–4 | 4–8 | 8–16 | 16–30 | 30–50 | 50–100 |
| *Wetness* | | | | | | | |
| Drainage class[b] | *A. nilotica*, *P. juliflora* | E, S, W, M | | I | P | V | |
| Drainage class[b] | *E. camald.* | E, S, W, M, I | P | V | | | |
| *Physical soil characteristics* | | | | | | | |
| Gravel content (volume %) | All species | 0–3 | 3–15 | 15–35 | 35–55 | | 55–100 |
| $CaCO_3$ (%) | *A. nilotica*, *P. juliflora* | 0–20 | 20–30 | 30–40 | 40–60 | 60–100 | |
| $CaCO_3$ (%) | *E. camald.* | 0–6 | 6–15 | 15–25 | 25–35 | 35–100 | |
| Gypsum (%) | All species | 0–3 | 3–5 | 5–10 | 10–20 | | 20–100 |
| Texture class[c] | *A. nilotica* | 6, 7, 9, 10, 11 | 4, 5, 8, 12 | 1, 2, 3, 13 | | | |
| Texture class[c] | *E. camald.* | 4, 6, 7, 9, 10, 11 | 5, 8, 12 | 2 | 3 | 1, 13 | |
| Texture class[c] | *P. juliflora* | 4, 5, 6, 7, 8, 9, 10, 11, 12 | 2, 3 | 1, 13 | | | |
| *Chemical soil characteristics* | | | | | | | |
| Cation exchange capacity of clay fraction/cmol $kg^{-1}$ clay | All species | ≥24 | 16–24 | | <16 | | |
| Base saturation (%) | All species | 50–100 | 35–50 | 20–35 | 0–20 | | |
| Total exchangeable bases/cmol $kg^{-1}$ soil | All species | ≥4.0 | 2.8–4.0 | 1.6–2.8 | 0.0–1.6 | | |
| Organic carbon (%) | *E. camald.*, *A. nilotica* | ≥1 | 0.4–1.0 | 0.1–0.4 | 0.01–0.1 | 0–0.01 | |
| Organic carbon (%) | *P. juliflora* | ≥1 | 0.2–1.0 | 0.1–0.2 | 0.01–0.1 | 0–0.01 | |
| pH $H_2O$ | *A. nilotica* | 7.0–7.5 | 5.5–7.0, 7.5–8.5 | 4.0–5.5, 8.5–9.0 | 3.0–4.0, 9.0–9.4 | 9.4–9.8 | <3.0, >9.8 |
| pH $H_2O$ | *E. camald.* | 6.5–7.5 | 5.5–6.5, 7.5–8.7 | 4.5–5.5, 8.7–9.0 | 3.5–4.5, 9.0–9.2 | 3.0–3.5, 9.2–9.4 | <3.0, >9.4 |
| pH $H_2O$ | *P. juliflora* | 6.7–8.1 | 5.5–6.7, 8.1–8.7 | 4.0–5.5, 8.1–9.2 | 3.0–4.0, 9.2–9.5 | 9.5–10.2 | <3.0, >10.2 |
| *Degree of salinity–alkalinity* | | | | | | | |
| ECe/ds $m^{-1}$ | *A. nilotica* | 0.0–3.8 | 3.8–7.2 | 5.2–11.3 | 11.3–16.1 | 16.1–19.8 | >19.8 |
| ECe/ds $m^{-1}$ | *E. camald.* | 0.0–2.0 | 2.0–8.0 | 8.0–12.0 | 12.0–14.0 | 14.0–16.0 | >16.0 |
| ECe/ds $m^{-1}$ | *P. juliflora* | 0.0–3.0 | 3.0–6.1 | 6.1–14.0 | 14.0–20.3 | 20.3–25.0 | >25.0 |
| ESP (%)[d] | *A. nilotica* | 0–60 | >60 | | | | |
| ESP (%)[d] | *E. camald.* | 0–50 | >50 | | | | |
| ESP (%)[d] | *P. juliflora* | 0–70 | >70 | | | | |

[a] *A. nilotica*—*Acacia nilotica*, *E. camald.*—*Eucalyptus camaldulensis*, *P. juliflora*—*Proposis juliflora*, All species—*Acacia nilotica*, *Eucalyptus camaldulensis*, and *Proposis juliflora*. [b] Drainage classes:[62] E—excessively drained, S—somewhat excessively drained, W—well drained, M—moderately well drained, I—imperfectly drained, P—poorly drained, V—very poorly drained. [c] Texture class:[62] 1—clay (heavy), 2—silty clay, 3—clay, 4—silty clay loam, 5—clay loam, 6—silt, 7—silt loam, 8—sandy clay, 9—loam, 10—sandy clay loam, 11—sandy loam, 12—loamy sand, 13—sand. [d] Nearly all semi-arid and arid soils with high ESP (sodic soils) also have a high pH value.[63] If stringent tree requirements for both pH and ESP are applied, the effect of pH and ESP on the yield would be double counted. As a result, the ESP requirements are made less restrictive.

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**Table 3** Climate requirements for *Eucalyptus camaldulensis*, *Acacia nilotica* and *Prosopis juliflora*[26]

| | | Rating | | | | | |
|---|---|---|---|---|---|---|---|
| Climate Characteristics | Species[a] | 100 | 90 | 72.5 | 50 | 32.5 | 0 |
| *Rainfall*[b] | | | | | | | |
| Annual precipitation/mm | *A. nilotica* | ≥1200 | 1000–1200 | 750–1000 | 500–750 | 200–500 | 0–200 |
| Annual precipitation/mm | *E. camald.* | ≥2500 | 1000–2500 | 600–1000 | 400–600 | 250–400 | 0–250 |
| Annual precipitation/mm | *P. juliflora* | ≥1200 | 750–1200 | 550–750 | 300–550 | 100–300 | 0–100 |
| | | Rating | | | | | |
| | | 100 | 90 | 72.5 | 50 | 32.5 | 12.5 |
| Length of dry season/months[c] | *A. nilotica* | 0–6 | 6–7 | 7–8 | 8–9 | 9–10 | 10–12 |
| Length of dry season/months[c] | *E. camald.* | 0–1 | 1–2 | 2–4 | 4–7 | 7–8 | 8–12 |
| Length of dry season/months[c] | *P. juliflora* | 0–6 | 6–7 | 7–8 | 8–10 | 10–11 | 11–12 |
| *Temperature* | | | | | | | |
| Mean max temp./°C | *A. nilotica* | 25–28 | 28–39 | 39–47 | 47–50 | 50–55 | >55 |
| Mean max temp./°C | *E. camald.* | 22–30 | 30–35 | 35–41 | 41–44 | 44–47.5 | >47.5 |
| Mean max temp./°C | *P. juliflora* | 20–30 | 30–34 | 34–42 | 42–50 | 50–55 | >55 |
| Mean annual temp./°C | *A. nilotica* | 24–28 | 19–24, 28–34 | 17–19, 34–39 | 15–17, 39–45 | 13–15, 45–50 | <13, >50 |
| Mean annual temp./°C | *E. camald.* | 20–24 | 24–26, 18–20 | 26–29, 15–18 | 29–32, 12–15 | 32–38, 7–12 | >38, <7 |
| Mean annual temp./°C | *P. juliflora* | 20–30 | 30–35, 18–20 | 35–38, 16–18 | 38–42, 14–16 | 42–45, 12–14 | >45, <12 |
| Mean min temp./°C | *A. nilotica* | 19–25 | 25–34, 15–19 | 10–15 | 6–10 | 4–6 | <4 |
| Mean min. temp./°C | *E. camald.* | 18–24 | 24–28, 14–18 | 10–14 | 7–10 | 1–7 | <1 |
| Mean min temp./°C | *P. juliflora* | 20–25 | 16–20, 25–35 | 12–16 | 8–12 | 5–8 | <5 |
| *Radiation* | | | | | | | |
| Fraction of sunshine hours | All species[a] | 0.7–1.0 | 0.5–0.7 | 0.0–0.5 | | | |

[a] *A. nilotica*—*Acacia nilotica*, *E. camald.*—*Eucalyptus camaldulensis*, *P. juliflora*—*Proposis juliflora*, All species—*Acacia nilotica*, *Eucalyptus camaldulensis*, *Proposis juliflora*. [b] The annual precipitation rating is not taken into account by Vashev *et al.*[26] because their study assumes that all water requirements are met by groundwater. This was done because salt-affected land is often located in arid and semi-arid regions where tree growth relies mainly on groundwater. However, as global groundwater datasets are not available, the present study assumes that water requirements are met by precipitation only. Therefore, in areas where groundwater tables are close to the surface, the potentials are underestimated. [c] The length of dry season (in months) is determined by comparing monthly precipitation (*P*) with monthly potential evapotranspiration (PET). When *P* is less than half of PET, the month is considered as part of the dry season.

analyses an average lower heating value of woody biomass of 18 GJ odt$^{-1}$ is assumed for all species.[47]

### 3.3. Production costs

The costs of establishment of forestry plantations in different world regions are taken from Strengers *et al.*[56] and vary between 320 and 506€ ha$^{-1}$ (Table 4). The costs of land rent are based on Hoogwijk *et al.*[48] but corrected by the ratio of average yields on salt-affected soils (as determined in the present study to be 3.1 odt ha$^{-1}$ y$^{-1}$) and average forestry plantation yields (as determined in the global potential study of Hoogwijk *et al.*[48] to be 7.5 odt ha$^{-1}$ y$^{-1}$). The regional salt-affected land rent is presented in Table 4. An average cost of maintenance (excluding the cost of fertilizers) is estimated to be 30€ ha$^{-1}$ y$^{-1}$ based on studies by Riegelhaupt,[57] Lopez *et al.*,[58] and Guitart and Rodriguez.[59] Regional differences in maintenance costs are assumed to be similar to the regional differences in establishment costs. Thus, regional maintenance costs are determined by multiplying the average maintenance cost with the ratio of regional establishment cost to average establishment costs (Table 4). The fertilizer costs are calculated by assuming that the nutrients in the harvested biomass need to be replaced, whereby a nutrient content of 4.40 kg N odt$^{-1}$, 0.45 kg P odt$^{-1}$ and 2.70 kg K odt$^{-1}$ of wood, fertilizer factors of 1 kg N kg$^{-1}$ N, 2.3 kg $P_2O_5$ kg$^{-1}$ P and 1.2 kg $K_2O$ kg$^{-1}$ K,[47] and fertilizer costs from FAOSTAT[60] are applied. To determine the harvesting costs, labor requirements and machinery costs of the three harvest systems are defined as shown in Table 5. Country-specific data on the price of labor are taken from LabourSTA.[61] A minimum price of labor of 0.25€ h$^{-1}$ is assumed.

**Table 4** Land rent, establishment and maintenance costs, per world region[a]

| | Land rent[b] € ha$^{-1}$ y$^{-1}$ | Establishment costs[56] € ha$^{-1}$ | Maintenance[57–59] € ha$^{-1}$ y$^{-1}$ |
|---|---|---|---|
| Canada | 24 | 426 | 31 |
| USA | 56 | 441 | 33 |
| C America | 46 | 506 | 37 |
| S America | 44 | 369 | 27 |
| N Africa | 10 | 426 | 31 |
| W Africa | 8 | 426 | 31 |
| E Africa | 7 | 320 | 24 |
| S Africa | 29 | 426 | 31 |
| W Europe | 47 | 329 | 24 |
| E Europe | 25 | 329 | 24 |
| F USSR | 10 | 363 | 27 |
| M East | 11 | 490 | 36 |
| S Asia | 47 | 490 | 36 |
| E Asia | 104 | 467 | 34 |
| SE Asia | 55 | 481 | 36 |
| Oceania | 5 | 369 | 27 |
| Japan | 247 | 326 | 24 |

[a] Definition of world regions is based on the IMAGE team.[49] [b] Land rent is based on data from Hoogwijk *et al.*[48] as described in the text.

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**Table 5** Labor input and machinery costs for harvest systems with different levels of mechanization (based on[45,46,64–67])

| Level of mechanization | Labor input h odt$^{-1}$ | Machinery costs € odt$^{-1}$ |
|---|---|---|
| Manual | 15.0 | 0.7 |
| Intermediate | 8.6 | 3.9 |
| Fully mechanized | 0.5 | 32.7 |

## 4. Results

### 4.1. Extent and location of salt-affected areas

The global extent of salt-affected land, as calculated from the HWSD, amounts to 1128 Mha (Table 6). This is slightly higher than previous estimates. For example, Szabolcs[68] estimates salt-affected land to be 955 Mha and FAO[13] 831 Mha. Insufficient information is available to determine the exact reasons for these discrepancies but such reasons could include different definitions of salt-affectedness and the application of different soil datasets. Global salt-affected soils are mainly saline, amounting to 60% of all salt-affected soils (Table 6). Sodic soils account for 26% and saline-sodic soils for 14%. The majority of salt-affected soils is slightly affected (65%), followed by 20% moderately, 10% extremely, and 5% highly salt-affected soils.

The mapping of salt-affected land shows that in nearly all world regions salt-affected soils are found, although the extent and severity vary among regions (Fig. 1 and Table 7). Regions with the largest salt-affected land areas are the Middle East (189 Mha), Australia (169 Mha), North Africa (144 Mha), and the former USSR (126 Mha) (Table 7). Excluding forests, wetlands, unsuitable areas, and (inter)nationally protected areas results in 971 Mha (or 86% of the total extent of salt-affected land) available for consideration in the analysis of the potentials (Table 7).

### 4.2. The global technical biomass production potential from salt-affected areas

Biomass yields on salt-affected soils (Fig. 2) range between 0 and 27 odt ha$^{-1}$ y$^{-1}$ with the average yield being 3.1 odt ha$^{-1}$ y$^{-1}$. Yield differences are explained primarily by the severity of salt-affectedness (see Fig. 1), but climate, particularly precipitation, is obviously an important factor as well.

**Table 6** The extent of salt-affected soils, by type and severity of salt-affectedness

| | | Type | | | | |
|---|---|---|---|---|---|---|
| Severity level | Unit | Saline | Sodic | Saline-sodic | Total[a] | Share (%) |
| Slight | 1000 ha | 606 | 124 | 6 | 735 | 65 |
| Moderate | 1000 ha | 69 | 147 | 11 | 228 | 20 |
| High | 1000 ha | 4 | 13 | 36 | 52 | 5 |
| Extreme | 1000 ha | 4 | 5 | 105 | 113 | 10 |
| Total[a] | 1000 ha | 683 | 288 | 157 | 1128 | |
| Share | % | 60 | 26 | 14 | | |

[a] Rows and columns may not actually sum to the given total due to rounding.

The total global technical biomass production potential of biosaline forestry is calculated to be 56 EJ y$^{-1}$ (3114 million odt y$^{-1}$) (Table 7), which represents approximately 11% of the current global primary energy use of approximately 514 EJ y$^{-1}$.[69] The regional breakdown of the technical potential shows that Oceania has the highest potential with 20 EJ y$^{-1}$, which is followed by the former USSR region with 10 EJ y$^{-1}$, South America with 5 EJ y$^{-1}$, and East Africa with 5 EJ y$^{-1}$ (Table 7). The high potential in Australia is primarily due to the very large amount of land that is salt-affected (169 Mha, Table 7), most of which is only slightly salt-affected. The low severity partially explains an average yield (7.6 odt ha$^{-1}$ y$^{-1}$) in Australia that is more than twice the global average yield on salt-affected land.

The breakdown of the potential by severity level and land use/cover class indicates that the largest potentials can be found on slightly and moderately affected areas that are currently covered by shrubs and herbaceous vegetation (68%) (Table 8). 26% of the potential comes from agricultural land, which is primarily slightly and moderately salt-affected. Thus, if current agricultural land is considered unavailable for biomass production because of sustainability concerns, the technical potential decreases to 42 EJ y$^{-1}$. Highly and extremely salt-affected soils combined account for only 6% (or 4 EJ y$^{-1}$) of the technical potential (Table 8). The technical potential broken down by land use/cover classes, severity levels, and the 17 world regions is presented in Table S1†.

### 4.3. Global economic biomass production potential from salt-affected areas

The average production cost of tree biomass from salt-affected soils is 4.0€ GJ$^{-1}$, but large regional and intraregional differences in production costs exist (Fig. 3).

The global economic potential analysis for biomass production on salt-affected soils indicates that there is an economic potential of biomass production from salt-affected soils (when including agricultural land) of 21 EJ y$^{-1}$ (or 4% of global primary energy consumption) at production costs of 2€ GJ$^{-1}$ or less (Table 7). The economic potential increases significantly, to 53 EJ y$^{-1}$, when biomass produced at costs of 5€ GJ$^{-1}$ or less are included. If agricultural land is excluded, the economic potential of biosaline forestry decreases to 12 EJ y$^{-1}$ at production costs of 2€ GJ$^{-1}$ or less and to 39 EJ y$^{-1}$ at production costs of 5€ GJ$^{-1}$ or less.

Global cost–supply curves by severity of affectedness (Fig. 4(a)) confirm that the largest share of the potential comes from the least salt-affected soils. Of the 21 EJ y$^{-1}$ at production costs of 2€ GJ$^{-1}$ or less, 19 EJ y$^{-1}$ (88%) are from slightly and moderately salt-affected soils while only 2 EJ y$^{-1}$ are from highly or extremely salt-affected soils. This trend is even more extreme for the economic potential at production costs of 5€ GJ$^{-1}$ or less, where slightly and moderately affected soils account for 93% of the potential. The global cost–supply curves by land use/cover class (Fig. 4(b)) indicate that biomass production on salt-affected land with shrub and herbaceous cover has the highest economic potential at production costs up to both 2€ GJ$^{-1}$ and 5€ GJ$^{-1}$.

The results also show that biomass production from biosaline forestry plantations may be economically feasible in various regions and may contribute to local and regional biomass and/or

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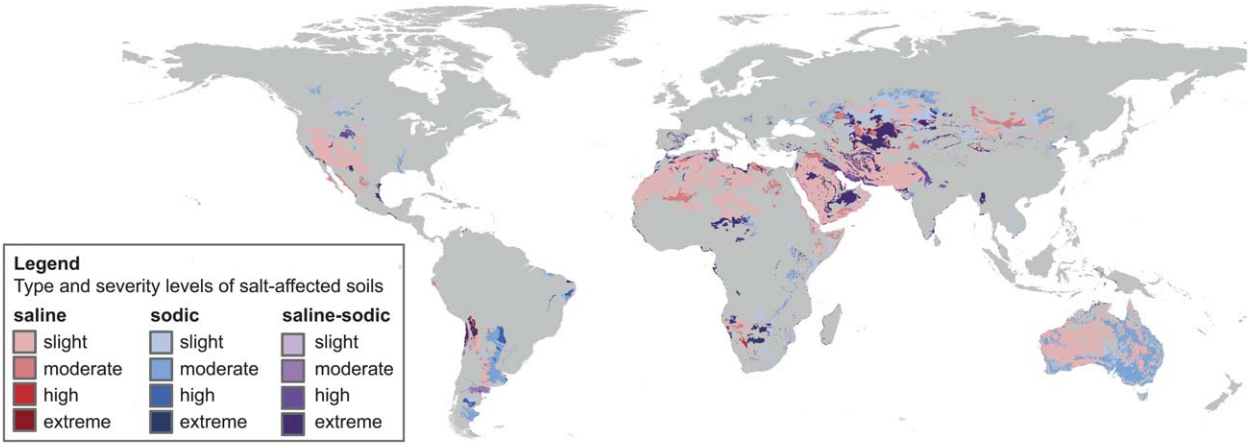

**Fig. 1** Global salt-affected soils, by type and severity (based on data from the HWSD[25]). (This map indicates the location of salt-affected soils worldwide but does not properly represent their areal extent as a result of multiple soil units per mapping unit of the HWSD. Multiple soil units are defined because mapping units are not generally homogeneous in soil characteristics. Up to nine soil units may be defined per mapping unit, and the map depicts the whole mapping unit to be salt-affected even if only one of the soil units is salt-affected. For the areal extent of salt-affected soils see Table 6.)

energy needs (Table 7). In particular, taking Africa as a whole shows that the biosaline forestry potential of 8 EJ $\text{y}^{-1}$ is approximately 28% of the total energy consumption (27 EJ $\text{y}^{-1}$ in 2007)[69] at production costs of 2€ $\text{GJ}^{-1}$ or less.

## 5. Discussion

The availability of salt-affected land for biosaline forestry is determined in this study by its current land use/land cover and the extent of areas of high biodiversity. Agricultural land (including cropland and pastureland) is not excluded in the potential analyses because conversion to a forestry plantation may prevent further salinization/sodification of the land and may even provide soil improvements.[39–42] This study found that agricultural land accounts for 26% of the technical potential. However, the effect of agriculture on land availability may be even larger considering that extensive agricultural land use, such as livestock grazing, commonly takes place on land with shrub and herbaceous cover and is not demarcated as such in the land use/cover dataset applied in this study, namely GLC2000.[50] Pastureland is not accounted for in this study because seasonal and inter-annual variability in grazing (and grazing intensity)

**Table 7** The extent of salt-affected soils and the technical and economic biomass production potential, by region

| | Salt-affected land | Salt-affected land excl. forest, wetlands, unsuitable, high biodiversity areas | Technical potential[b] | Economic potential | |
|---|---|---|---|---|---|
| | | | | ≤2 € $\text{GJ}^{-1}$ | ≤5 € $\text{GJ}^{-1}$ |
| Region | Mha | Mha | EJ $\text{y}^{-1}$ | EJ $\text{y}^{-1}$ | EJ $\text{y}^{-1}$ |
| Canada | 7 | 5 | 0.7 | 0.0 | 0.7 |
| USA | 77 | 58 | 2.9 | 0.0 | 2.0 |
| Central America | 5 | 4 | 0.3 | 0.0 | 0.2 |
| South America | 84 | 57 | 5.4 | 3.7 | 4.9 |
| North Africa | 161 | 157 | 1.1 | 0.6 | 1.1 |
| West Africa | 83 | 76 | 0.8 | 0.7 | 0.8 |
| East Africa | 56 | 43 | 5.1 | 5.0 | 5.1 |
| South Africa | 22 | 19 | 2.0 | 1.2 | 1.9 |
| West Europe | 1 | 1 | 0.0 | 0.0 | 0.0 |
| East Europe | 2 | 1 | 0.2 | 0.0 | 0.2 |
| Former USSR | 126 | 117 | 10.0 | 6.3 | 9.7 |
| Middle East | 176 | 158 | 1.8 | 0.6 | 1.5 |
| South Asia | 52 | 45 | 2.8 | 2.4 | 2.7 |
| East Asia | 98 | 83 | 2.6 | 0.0 | 2.1 |
| Southeast Asia | 6 | 5 | 0.5 | 0.2 | 0.5 |
| Oceania | 169 | 144 | 20.2 | 0.0 | 19.7 |
| Japan | 0 | 0 | 0.0 | 0.0 | 0.0 |
| World[a] | 1128 | 971 | 56.2 | 20.8 | 52.8 |

[a] Columns may not actually sum to the given total due to rounding. [b] The technical and economic potential refers to salt-affected land not classified as forests, wetlands, unsuitable areas, or (inter)nationally protected areas.

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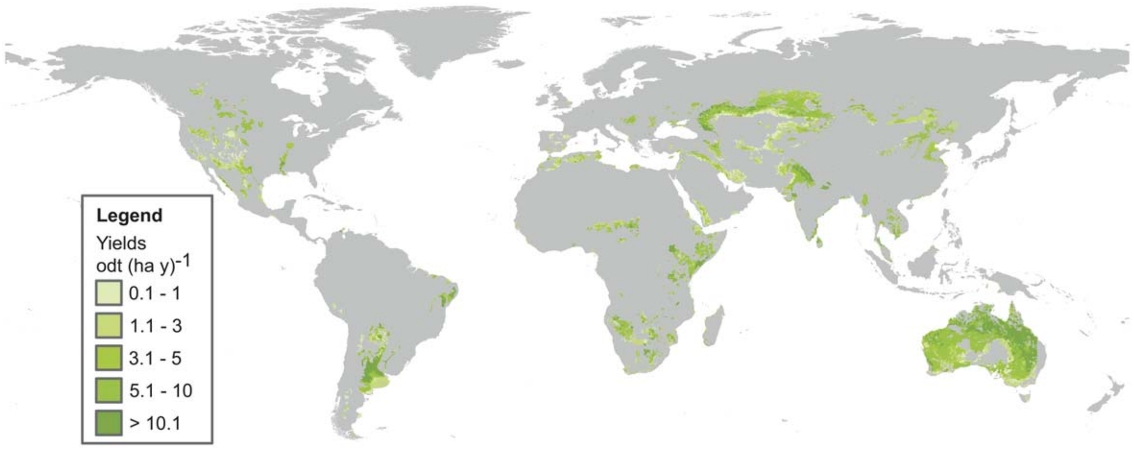

**Fig. 2** Modeled yields on salt-affected soils.

**Table 8** The technical biomass production potential, by severity level and land use/cover class

| | Severity level | | | | Total[a] | Share |
|---|---|---|---|---|---|---|
| Land use/cover | Slight EJ $y^{-1}$ | Moderate EJ $y^{-1}$ | High EJ $y^{-1}$ | Extreme EJ $y^{-1}$ | EJ $y^{-1}$ | % |
| Agriculture | 7.9 | 4.8 | 1.3 | 0.6 | 14.6 | 26 |
| Bare areas | 2.2 | 0.7 | 0.1 | 0.4 | 3.4 | 6 |
| Shrub and herbaceous cover | 26.8 | 10.2 | 0.5 | 0.8 | 38.3 | 68 |
| Total[a] | 36.8 | 15.7 | 1.9 | 1.8 | 56.2 | |
| Share (%) | 65 | 28 | 3 | 3 | | |

[a] Rows and columns may not actually sum to the given total due to rounding.

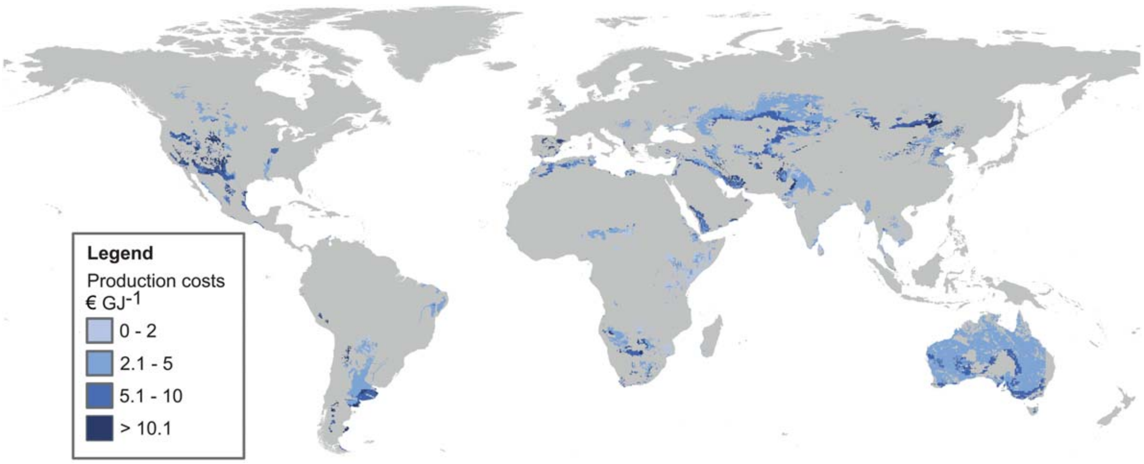

**Fig. 3** Production costs of woody biomass from salt-affected soils.

and the low quality of census data on pastureland make this land use difficult to demarcate.[70] In addition, (over)grazing can cause further soil degradation and may, therefore, not be desirable on already salt-affected or other degraded land. Nevertheless, an approximation of the potential effect of excluding pastureland from availability for biosaline forestry can be made by applying Ramankutty *et al.*'s dataset on pastureland.[70] This approximation shows that 18% (11 EJ $y^{-1}$) of the technical potential originates from pastureland that is not yet accounted for by the GLC2000. However, biomass production on salt-affected soils can be combined with food and feed/forage production in agroforestry and silvopastoral systems by, for example, intercropping, rotational woodlots, and hedgerows. The potential of such combined systems should also be assessed given that they may be more preferable with respect to ensuring food security and increasing biodiversity and more research is needed to improve data quality of pastureland use and maps. In addition to current land use/cover, it is also important to account for future

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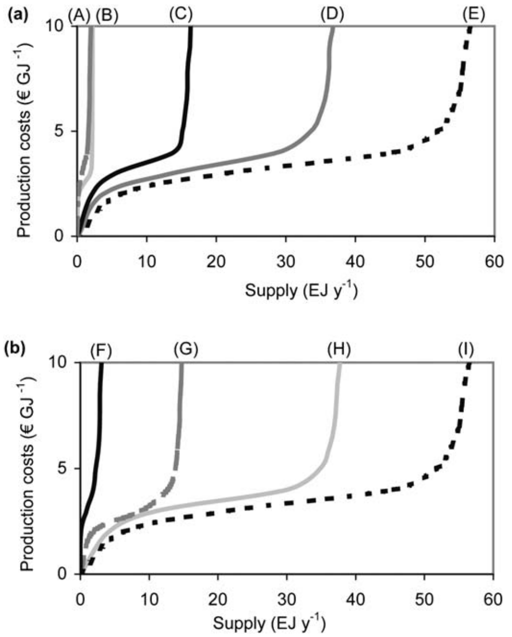

**Fig. 4** Global cost–supply curves for salt-affected soils, by (a) severity and (b) land use/cover. Severity levels: (A) extreme; (B) high; (C) moderate; (D) slight and (E) total. Land use/cover classes: (F) bare areas; (G) agriculture; (H) shrub and herbaceous cover, and (I) total.

developments in land use and the impact on the extent and availability of salt-affected land for biosaline forestry. An important factor in future land use and land use change is likely to be the increasing demand for land for agricultural production to meet the growing world population's demand for food and dietary changes. As highly productive land becomes scarcer, agriculture may have to increasingly rely on low productive and degraded (including salt-affected) land and may reduce the availability for biosaline forestry. In addition to current land use/cover as an indicator of the (un)availability of salt-affected land, salt-affected land may also be considered unavailable as a result of high biodiversity. This study accounted for high biodiversity areas by excluding nationally and internationally protected areas. However, little is known about the actual biodiversity levels of salt-affected land. Future research should assess this aspect and its implications for the sustainability of biomass production on salt-affected land in more detail. Moreover, future policies on biodiversity restoration and conservation and on forestry can lead to a reduction in the available land area. Combined with increased labor and land costs, this can lead to a reduction of the technical and economic bioenergy potential of salt-affected soils. Climate change can lead to either moderation or acceleration of soil salinization and sodification depending on local conditions such as groundwater depth and quality.[71]

Data availability for determining the yields on salt-affected land, particularly for defining the tree requirements and the constraint-free yields, is a limiting factor. For example, the rating for salinity is based on salinity curves for the juvenile stage of the trees because of the limited availability of salinity curves for tree growth in later stages. However, since trees are generally more susceptible to salts in the juvenile stage than in later stages,[39] applying the juvenile curve results in lower calculated yields than what is potentially possible. Given that this is the most important variable for saline soils, more work on salinity (and sodicity) curves for later stages is required in order to determine the effect on yields and potential. For the tropical yield model, three land characteristics used in Vashev *et al.*'s model[26] could not be accounted for in this global study due to the lack of global datasets needed to map them. These are flooding, soil depth, and groundwater depth. Groundwater depth is particularly crucial for tree biomass production in salt-affected environments[26] because salt-affected soils in (sub)tropical regions occur primarily in semi-arid or arid regions where tree growth depends more on groundwater than on precipitation. Therefore, in areas with water tables close to the surface, this study underestimates yields and, consequently, potentials. Future research could further address this shortcoming by, for example, generating a simple global groundwater indicator map and applying it to the global model. Such a map may be generated by combining existing information from geomorphologic maps and drainage network maps. However, this would still only be an approximation of global groundwater levels; more reliable groundwater maps are desirable in the long run. Constraint-free yields for the (sub)tropical tree species are approximated by the highest yield recorded in the literature because constraint-free yield data are not available. This approach underestimates the constraint-free yield and, thereby, results in conservative estimates of actual yields.

Forestry plantation management specific to (different types and severity levels of) salt-affected soils is not included in this study because of the limited data on the precise effects of certain management techniques and of above- and belowground biomass growth on the soil characteristics and, thereby, on the yields. Although an increase in yields and technical potential is likely as a result of improved management, it is unclear whether the economic potential also increases. This is because additional management raises per-hectare production costs. Furthermore, using a generalized forestry production system to estimate the biomass yields (and production costs) ignores the impact of differences in management requirements for different species and soil and climate conditions. The impact of these aspects on the yield and production costs should be a central topic for further research.

## 6. Conclusions

The results of this analysis indicate that salt-affected soils cover approximately 1.1 Gha worldwide, of which 14% is classified as forest, wetlands or (inter)nationally protected areas and is considered unavailable for biomass production because of sustainability concerns. For the remaining salt-affected area, this study finds an average biomass yield of 3.1 oven dry ton ha$^{-1}$ y$^{-1}$ and a global technical potential of 56 EJ y$^{-1}$, or 11% of the current global primary energy consumption. A significant part of the technical potential comes from agricultural land, and its conversion to biomass production may not be considered sustainable. If current agricultural land is also considered unavailable because of sustainability concerns, the technical potential decreases to 42 EJ y$^{-1}$. The analysis of current land use/cover of salt-affected soils indicates that the lowest production costs and largest potentials are found on land that is currently

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under shrub and herbaceous cover. However, land from this category is often used for livestock grazing and may therefore only partly be available for biomass production, although agroforestry systems that combine livestock grazing (or agricultural crop production) and biomass production are possible and may actually prevent further salinization/sodification of the land. In order to avoid competition with feed/forage production, future assessments must investigate this topic more carefully.

The global economic potential of biosaline forestry at production costs of 2€ $GJ^{-1}$ or less is calculated to be 21 EJ $y^{-1}$ (equivalent to 4% of current global energy consumption) when including agricultural land and 12 EJ $y^{-1}$ when excluding agricultural land. At production costs of up to 5€ $GJ^{-1}$, the global economic potential increases to 53 EJ $y^{-1}$ when including agricultural land and to 39 EJ $y^{-1}$ when excluding agricultural land. Global cost–supply curves by severity of salt-affectedness confirm that the largest share of potential comes from the least salt-affected soils. Of the 21 EJ $y^{-1}$ at production costs of 2€ $GJ^{-1}$ or less, 19 EJ $y^{-1}$ are from slightly and moderately salt-affected soils while only 2 EJ $y^{-1}$ are from highly or extremely salt-affected soils. This trend is even more extreme for the economic potential at production costs of 5€ $GJ^{-1}$ or less, where slightly and moderately affected soils account for 93% of the potential.

This study presents an initial assessment of global bioenergy potential from salt-affected soils and indicates that biomass production on these soils could make a significant contribution to global and regional (bio-)energy supply. Several aspects require additional research. Future research in the field of biosaline forestry should focus on the current use of salt-affected land, on how management affects yields and production costs, on the economic feasibility of biosaline forestry, and on how biosaline forestry (and agroforestry) can be promoted. In addition, biosaline forestry has numerous additional benefits such as the potential to improve soil, generate income from previously low-productive or unproductive land, and soil carbon sequestration. These are important additional reasons for investigating and investing in biosaline forestry.

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