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Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials

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ABSTRACT

IIASA's agro-ecological zones modelling framework has been extended for biofuel productivity assessments distinguishing five main groups of feedstocks covering a wide range of agronomic conditions and energy production pathways, namely: woody lignocellulosic plants, herbaceous lignocellulosic plants, oil crops, starch crops and sugar crops. A uniform Pan-European land resources database was compiled at the spatial resolution of 1 km^2. Suitability and productivity assessments were carried out by matching climate characteristics with plant requirements, calculating annual biomass increments or yields including consideration of soil and terrain characteristics of each grid-cell.

Potential biomass productivity and associated energy yields were calculated for each grid-cell. Spatial distributions of suitabilities of biofuel feedstocks in Europe were generated for each individual feedstock as well as for the five biofuel feedstock groups. Estimated agronomical attainable yields, both in terms of biomass (kg ha^{-1}) as well as biofuel energy equivalent (GJ ha^{-1}), were mapped and tabulated by agriculture and pasture land cover classes as derived from the CORINE land cover database. Results have been further aggregated by administrative units at NUTS 2 level.

1. Introduction

EU member states began to implement various policy measures to promote the use of biomass including biofuels [1,2]. For 2020 a proposal of a new directive on renewable energy is currently being discussed including a 10% biofuels shares in transport [3]. In December 2008 an informal compromise between the European Parliament and the Council's Presidency revised the 10% target towards inclusion of all renewable energies in the transport sector (i.e. in addition to biofuels, renewable electricity for trains and electric cars will be counted). In addition 2nd generation biofuels produced from waste, or non-food cellulosic and lignocellulosic biomass will be double credited towards the 10% target [5]. In 2007 biofuel consumption in the EU was 7.7 Mtoe representing 2.6% of the energy content of total road transport fuel use [6].

Most current biofuel production processes follow so-called 1st generation conversion pathways relying on sugar, starch, or vegetable oil components of crops. Crop production and

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List of acronyms

AEZ	agro-ecological zones
CAP	common agricultural policy
EU	European Union
GHG	greenhouse gas
LUT	land utilization types

conversion to biofuels usually requires fossil energy. The 1st generation pathway provides greenhouse gas reductions from ''well-to-wheels'' in the range of 20–70% as compared with petroleum fuels [7]. Extensive use of biofuels requires expansion of the range of feedstocks and the introduction of advanced conversion technologies such as Fischer–Tropsch synthesis, and ethanol production from lignocellulosic feedstocks using a biochemical route. This 2nd generation biofuel production pathway can convert most of a plant's biomass including the cellulosic parts to biofuels with relative low net greenhouse gas emissions. First generation biofuel production is extensively employed in Brazil (sugarcane for bioethanol), in the United States (cereals for bioethanol) and in Europe (oilseeds for biodiesel); 2nd generation production is up to now only available at a demonstration scale.

Main factors determining a country's technical domestic biofuel energy potentials include land availability, yields of biofuel feedstocks, and efficiency of conversion technologies applied. Europe's domestic bioenergy production potential has been estimated in several studies [8–11]. Conversion from biomass to energy is usually based on average biomass yields of the bioenergy feedstock considered and largely ignores the wide variability of potential productivity of biofuel feedstocks due to spatial characteristics of biophysical conditions and management regimes. This paper presents a spatially detailed feedstock suitability and productivity assessment for a wide range of land utilization types, including feedstocks for 1st and 2nd generation biofuels, and provides a regional specification of Europe's biofuel production potential. For this purpose the agro-ecological zones (AEZ) modelling framework has been expanded and enhanced for feedstock productivity assessments.

Section 2 describes data and methodology including the compilation of a Pan-European natural resources database at 1 km grid-cell resolution. This special natural resources database provides a key input for the biofuel feedstock assessment. Results are presented in Section 3 and include maps and tabulated country results by major feedstock groups for both physical biomass yields (in kg ha^{-1}) and estimates of energy yields expressed in biofuel equivalent. Section 4, discussion, focuses on environment and biofuel feedstock production and a comparison of the 1st versus 2nd generation production pathways, especially from a farmers' perspective. The final section presents conclusions.

2. Assessment of land potentials for biofuel feedstock production

The agro-ecological zones (AEZ) modelling framework has been expanded to include all major types of temperate biofuel feedstocks, estimating suitability and potential productivity for biofuel crops, perennial grasses and trees species on a grid-cell basis [12,13] implemented on a European 1 km^2 grid. Published conversion factors were applied for comparing energy potentials in biofuel equivalents across different feedstock groups.

2.1. *Pan-European land resources database*

A comprehensive Pan-European natural resources database was compiled for the assessment of biofuel feedstock land suitability. Original spatial inventories were converted to a uniform one by one km grid in a Geographic Information System. The land resources inventory contains climate, topography, soil, and land use as main thematic layers.

- The *climatic inventory* has been compiled from gridded climate parameters available from Climate Research Unit at East Anglia University [14,15] and the VASCLimO global precipitation data from the Global Precipitation Climatology Centre [16].
- The NASA Shuttle Radar Topographic Mission (SRTM) provides *digital elevation data* as three arc second digital elevation models (DEM) [17]. Tiles of SRTM data covering the European continent were used for areas up to 60° latitude. For areas north of 60° latitude, where no SRTM data is available, elevation data from GTOPO30 [18] was used. *Slope gradients* were calculated and converted to slope class distributions in each 1 km grid-cell. Eight slope classes were used, namely: 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and >45%.
- The *soil data* are based on the European Soil Bureau Network (ESBN) [19], which has been expanded with soil data from the ISRIC/FAO/IIASA WISE database [20,21].
- Three *land cover databases* were used to generate an inventory with twelve major land use/land cover classes. These sources include (a) CORINE version (CLCC 2000) for EU 25 [22]; (b) CORINE Version 1990 (CLC1990) for Switzerland [23]; and (c) JRC's Global Land Cover for Europe (GLC2000) [24]. The 12 land cover categories are: (i) forest, (ii) natural grassland, (iii) wetlands, (iv) other natural vegetation, (v) arable land, (vi) permanent crops, (vii) hetrogenious agricultural land, (viii) pasture land, (ix) water, (x) bare or sparsely vegetated land, (xi) glaciers, snow, (xii) urban and industrial land. Four of those were earmarked for potential production of biofuel feedstock, namely class (v–viii). Fig. 1 presents the spatial pattern of the twelve major categories for Europe.
- *Protected areas* reflect an interpretation of the IUCN-WCMC protected areas inventory at 30-arc seconds, separating protected land where cultivation is permitted from areas where cultivation is strictly prohibited.

An *administrative* layer map has been included in the geographic information system. Administrative levels are defined to the NUTS 2 level for EU27, Switzerland and Norway. The administrative map in the Ukraine includes oblast level. For other European countries only national boundaries are shown.

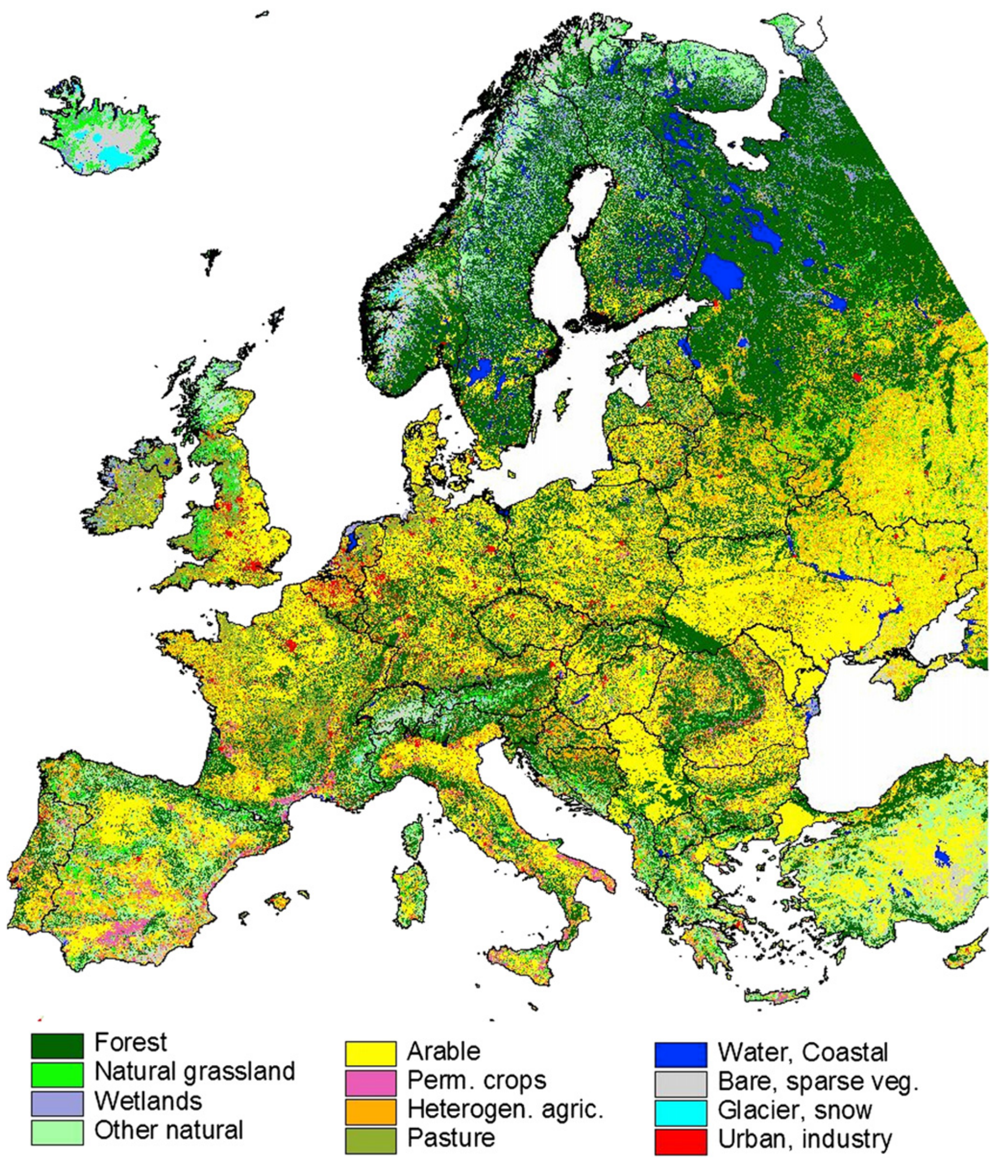

Fig. 1 – Major land use categories of the 1 × 1 km Pan-European land use database.

2.2. Biofuel feedstocks

We differentiate between 1st generation conversion, based respectively on biochemical conversion of biomass to ethanol via intermediates such as sugar, or based on vegetable oil for biodiesel, and 2nd generation biofuels based on biochemical processes or thermochemical conversion using combustion, gasification and conversion of syngas, or pyrolysis.

For the suitability and productivity assessments with the AEZ modelling framework, five main groups of land utilization types (LUT) with specific biofuel production pathways are distinguished, namely: Woody lignocellulosic plants, herbaceous lignocellulosic plants, oil crops, sugar crops and starch crops.

(1) Woody lignocellulosic plants – (2nd generation biofuels)

These LUTs include short rotation forestry management systems. Tree species considered include poplars, willows and eucalypts. The selected tree species cover a wide range of ecological regions of Europe.

- Poplar (*Populus nigra, Populus euramericana cv rob, Populus alba, Populus tremula, Populus balsamiferas Populus maximowiczii, Populus tomentosa, Populus euphraetica*)
- Willow (*Salix alba, Salix viminalis*)
- Eucalyptus (*E. globulus, E. camaldulensis, E. viminalis*)

(2) Herbaceous lignocellulosic plants – (2nd generation biofuels)

The herbaceous plants represented in this study include:

- Miscanthus (*Miscanthus sinensis*)
- Switch grass (*Panicum virgatum*)
- Reed canary grass (*Phalaris arundinaceae*)

(3) Oil crops – (1st generation biofuel for production of biodiesel)

The two selected oil crops are widely grown in respectively southern and central, and northern and central Europe.

- Sunflower (*Helianthus annuus*)
- Rapeseed (*Brassica napus oleifera*)

(4) Starch crops – (1st generation biofuel for production of bioethanol)

Selected cereals are wheat, maize, rye and triticale. Wheat and maize are widely grown, rye and triticale are (currently) much less grown but have similar potential for starch to energy conversion as wheat.

- Wheat (*Triticum aestivum*)
- Rye (*Secale cereale*)
- Triticale (*Tritico secale*)
- Maize (*Zea mays*)

(5) Sugar crops – (1st generation biofuel for production of bioethanol)

Sugar beet is a widely grown crop in Europe, while sweet sorghum is regarded as a potential energy crop for the sugar to energy production pathway.

- Sugar beet (*Beta vulgaris*)
- Sweet sorghum (*Sorghum bicolor*)

2.3. *Agro-ecological zones methodology*

The Food and Agriculture Organization of the United Nations (FAO), in collaboration with the International Institute for Applied Systems Analysis (IIASA), has developed the agro-ecological zones (AEZ) methodology [12] for the spatial assessment of production potentials of agricultural crops. For bioenergy assessments a companion model of AEZ has been developed that enables assessments of potential productivity of tree species as well [13].

AEZ follows an environmental approach. It provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to crops, perennial grasses and forest species production, and uses environmental matching procedures to identify limitations of prevailing climate, soil and terrain for assumed management objectives.

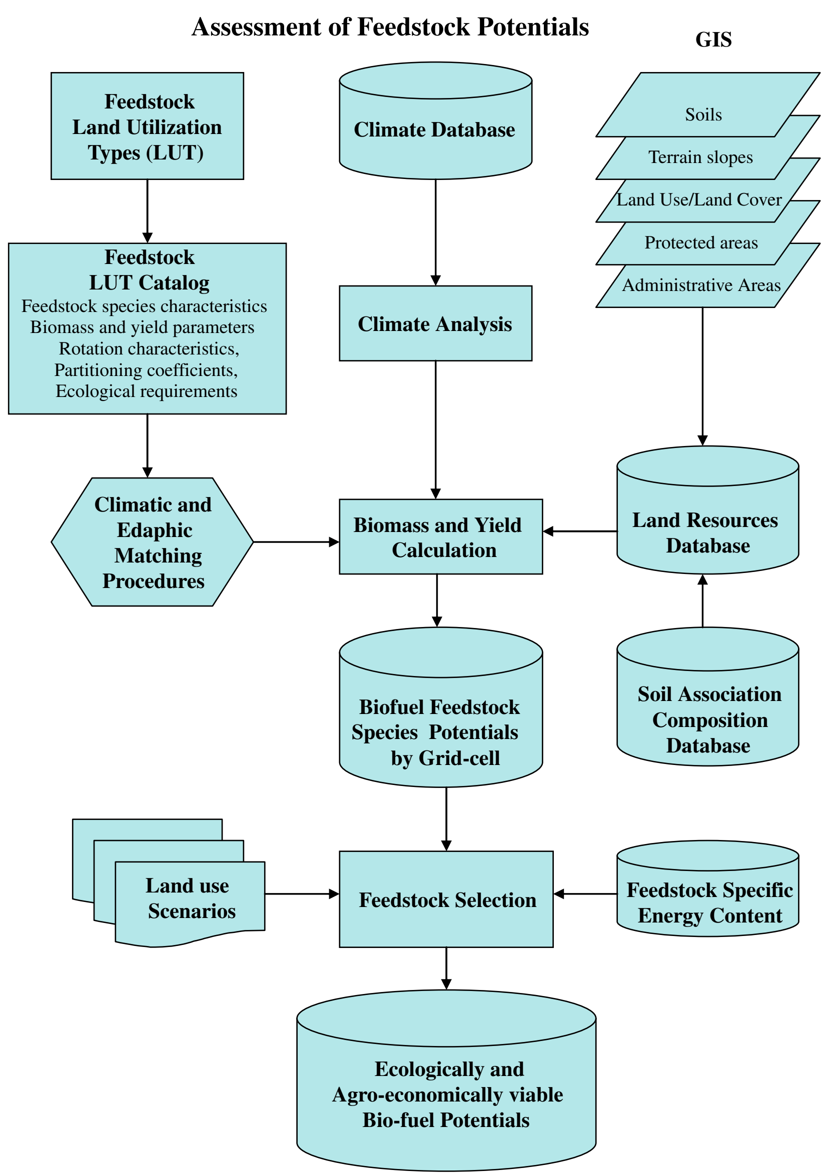

Fig. 2 – Agro-ecological zones (AEZ) methodology for assessment of biofuel feedstock potentials.

Box 1

Feedstock land utilization types (LUT)
The land utilization types include definitions and descriptions of biofuel feedstock crops, perennial grasses and tree species. The LUT attributes include characteristics of the feedstock species and information on management practices, inputs and utilization of produce.

Feedstock/LUT catalogue
The catalogue database provides a quantified description of LUTs including adaptability characteristics such as: rotation length, vegetation period, photosynthetic pathway, photosynthesis temperature relationships, maximum leaf area index, partitioning coefficients, and parameters describing ecological requirements of the selected biofuel crops, perennial grasses and tree species.

Climate database
Gridded climate parameters from East Anglia University (CRU global climatologies) and VASCLimO global precipitation data from the Global Precipitation Climatology Centre (GPCC) are used (see Section 2.2).

Soil association composition database
The soil association composition database contains ESBN soil attributes database expanded with additional soil parameters from the ISRIC/FAO/IIASA WISE database [20,21].

Land resources database and land characteristics (GIS)
The land resources database includes layers of the Soil Map of Europe, a slope distribution database, land cover layers, a protected areas layer and administrative areas, all with associated attribute databases (see Section 2.1).

Climate analysis
From basic climatic data, monthly reference evapotranspiration (ETo) has been calculated according to Penman–Monteith. A water-balance model provides estimations of actual evapotranspiration (ETa) and length of growing period (LGP). Temperature and elevation are used for the characterization of thermal regimes (TR) as follows: thermal climates, representing major latitudinal climatic zones; winter and summer temperatures and extreme temperatures; temperature growing periods (LGP_t), and accumulated temperatures. Temperature requirements of individual LUTs are matched with temperature regimes prevailing in individual grid-cells. For grid-cells with an optimum or sub-optimum match, calculations of annual biomass increments or yields are performed.

Biomass increment and yield calculations
The methodology for the calculation of potential biomass for crops is based on the AEZ eco-physiological biomass model. For tree species it is based on the combined Chapman–Richard biomass increment model, and the AEZ biomass model. It provides temperature and radiation based biomass production of individual crops and tree species.

Climatic suitability
Climatic constraints cause direct or indirect losses in the biomass increment. These agro- or sylvo-climatic constraints are influenced by the following conditions respectively:

Crops:
- The variability and degree of water-stress during the growing period.
- The yield-quality reducing factors of pests, diseases and weeds.
- The climatic factors, operating directly or indirectly, that reduce yield and quality of produce mainly through their effects on yield components and yield formation.
- The climatic factors which effect the efficiency of farming operations and costs of production. And
- The risk of occurrence of late and early frost.

Tree species:
- The variability and degree of water-stress during the growing period.
- Constraints indirectly related to climatic conditions (e.g., pests, diseases and invasion of unwanted species or weeds).
- The climatic factors which affect the efficiency of forestry operations and costs of production; and
- The risk of occurrence of late and early frost, and disturbance by fire.

Edaphic suitability
The edaphic suitability assessment is based on matching of soil and terrain requirements of biomass plant species with prevailing soil and terrain conditions. These are management and input specific.

The biofuel feedstock suitability and productivity assessments for Europe were carried out by matching characteristics of current climate with plant requirements, calculating annual biomass increments or yields, and subsequently, by comparing soil and terrain characteristics of each grid-cell with ecological requirements of the crops and tree LUTs considered. Fig. 2 and Box 1 present a schematic overview of the flow and integration as implemented.

3. Results – feedstock potentials

3.1. Biomass potential

Results of the suitability and productivity assessments were recorded by 1 km grid-cells for individual feedstock LUTs. Results refer to appropriate management with adequate fertilization and full mechanization based on currently available feedstock varieties. Woody and herbaceous plants for lignocellulosic conversion were assumed to be grown on surplus cultivated land and selected pastures (land cover classes v–viii), while 1st generation feedstocks obtained from agricultural crops were considered for use on surplus cultivated land only (land cover classes v–vii).

Suitability and yield maps for biofuel feedstocks in Europe were generated for all individual feedstock types as well as for the five biofuel feedstock groups. As an example oil crops are presented in Fig. 3.

Results illustrate the spatial patterns and variability of biofuel feedstock yields across Europe and provide a basis for assessing comparative advantages of specific biofuel feedstocks. It is assumed that biofuel feedstocks, in particular 1st generation types, will be included in multi-year crop rotations of food and feed crops. Results were tabulated by country and NUTS 2 levels providing average yields per administrative unit as well as distributions of land by suitability/productivity classes.

In the various maps, physical quantities (tonnes biomass ha^{-1}, kg oil ha^{-1}, kg sugar ha^{-1}) have been classified according to suitability classes as follows:

- VS very suitable (80–100% of maximum achievable yield in Europe);
- S suitable (60–80%);
- MS moderately suitable (40–60%);
- mS marginally suitable (20–40%);
- NS not suitable (less than 20% of maximum).

Table 1 summarizes for five European countries suitability distributions and associated yields. For instance, in Germany some 40% of the cultivated land is assessed as very suitable (VS) for herbaceous lignocellulosic feedstocks with an average yield of 16.6 t ha^{-1} dry weight, some 22% is suitable (S) with an average yield of about 13 t ha^{-1}, etc. The suitability and yields reflect the spatial distribution of the best-performing sub-types in each feedstock group and grid-cell.

3.2. Energy potentials

Feedstock biomass yields were converted to biofuel equivalents using the conversion factors shown in Table 2. Optimizing production in energy terms in each grid-cell

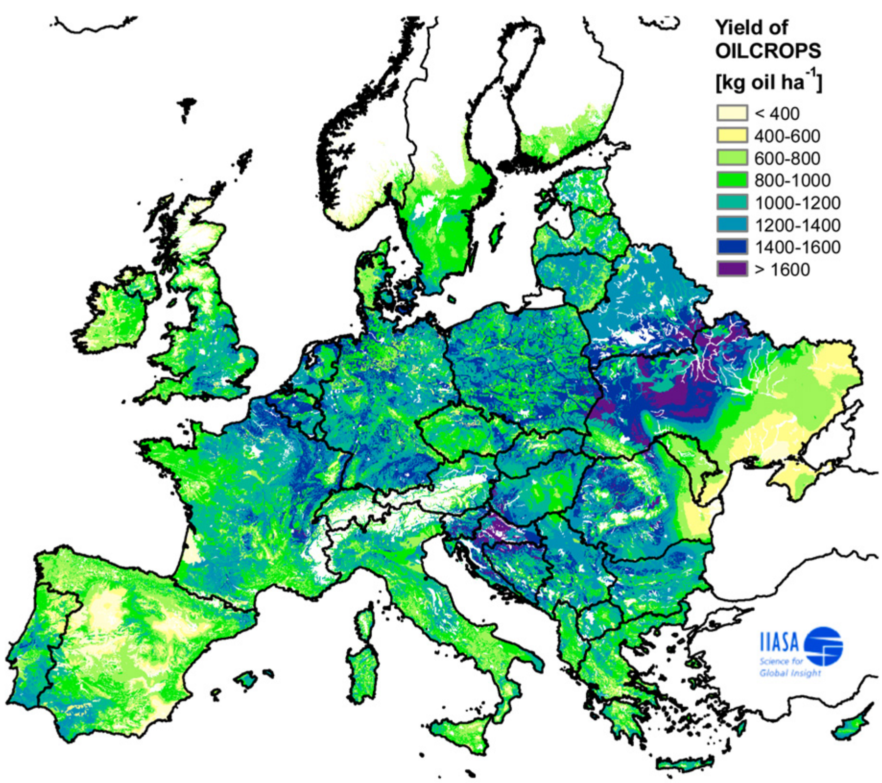

Fig. 3 – Potential yields of oil crops (rapeseed or sunflower) in Europe.

Table 1 – Biomass potentials of biofuel feedstocks for selected European countries.

Suitability class[b]	Suitability profiles of agricultural land[a] (%)					Average yield by suitability class				Yield specifications
	VS	S	MS	ms	NS	VS	S	MS	ms	
Germany										
Herbaceous	40	22	16	1	22	16.6	12.9	9.0	5.2	$t\,ha^{-1}$ AGB (DW)[c]
Woody	19	37	29	10	5	13.4	10.4	7.1	4.0	$t\,ha^{-1}$ AGB (DW)
Cereals	45	17	17	4	17	8.5	6.5	4.6	2.8	$t\,ha^{-1}$ grain (DW)
Sugar crops	28	22	13	9	28	8.3	6.5	4.5	2.6	$t\,ha^{-1}$ sugar (DW)
Oil crops	45	19	15	5	17	1.5	1.1	0.8	0.5	$t\,ha^{-1}$ oil
France										
Herbaceous	37	23	9	1	30	18.5	14.4	9.9	5.9	$t\,ha^{-1}$ AGB (DW)
Woody	53	24	9	3	12	15.4	10.8	7.1	3.5	$t\,ha^{-1}$ AGB (DW)
Cereals	39	21	13	6	12	7.2	5.9	4.0	2.7	$t\,ha^{-1}$ grain (DW)
Sugar crops	17	25	15	10	32	8.0	6.2	4.3	2.4	$t\,ha^{-1}$ sugar (DW)
Oil crops	24	28	14	6	28	1.4	1.1	0.8	0.5	$t\,ha^{-1}$ oil
Italy										
Herbaceous	14	23	15	6	43	19.5	14.7	10.2	6.3	$t\,ha^{-1}$ AGB (DW)
Woody	29	27	11	2	30	15.1	10.8	7.1	3.5	$t\,ha^{-1}$ AGB (DW)
Cereals	14	25	17	7	36	7.0	5.4	3.8	2.3	$t\,ha^{-1}$ grain (DW)
Sugar crops	8	18	14	11	49	8.0	6.0	4.1	2.4	$t\,ha^{-1}$ sugar (DW)
Oil crops	11	23	19	8	40	1.3	1.0	0.7	0.5	$t\,ha^{-1}$ oil
Great Britain										
Herbaceous	17	30	18	3	32	14.0	11.6	8.4	4.5	$t\,ha^{-1}$ AGB (DW)
Woody	15	23	17	11	34	13.2	10.0	6.7	3.6	$t\,ha^{-1}$ AGB (DW)
Cereals	10	34	25	6	26	7.1	6.2	4.4	2.7	$t\,ha^{-1}$ grain (DW)
Sugar crops	13	19	16	10	41	7.8	6.2	4.5	2.8	$t\,ha^{-1}$ sugar (DW)
Oil crops	20	27	19	9	24	1.4	1.1	0.8	0.5	$t\,ha^{-1}$ oil
Poland										
Herbaceous	33	10	18	0	39	17.1	13.3	9.4	5.4	$t\,ha^{-1}$ AGB (DW)
Woody	14	37	31	10	7	13.3	10.6	7.2	4.1	$t\,ha^{-1}$ AGB (DW)
Cereals	34	11	16	4	35	8.6	6.5	4.5	2.9	$t\,ha^{-1}$ grain (DW)
Sugar crops	25	17	14	6	38	8.6	6.7	4.5	2.6	$t\,ha^{-1}$ sugar (DW)
Oil crops	35	11	15	4	34	1.5	1.2	0.8	0.5	$t\,ha^{-1}$ oil

a Agricultural areas for herbaceous and woody lignocellulosic feedstocks include the following land use categories (as defined in the GIS land use database): arable, permanent crops, heterogeneous agriculture, permanent pastures, and natural grassland. For all other feedstocks only arable land, land used for permanent crops and the class of heterogeneous agriculture is included.
b Suitability classes: VS, very suitable; S, suitable; MS, moderately suitable; ms, marginally suitable; NS, not suitable.
c AGB, annual above ground biomass; DW, dry weight.

overall 1st and 2nd generation feedstocks provides maximum energy yields per hectare. While energy conversion factors from 1st generation feedstocks are relatively well established, those of 2nd generation technologies per unit of lignocellulosic feedstock are somewhat speculative in view of ongoing technological developments. The transition from demonstration scale to industrial scale has only recently started. The energy conversion factors for woody and herbaceous lignocellulosic biomass use as example the Fischer–Tropsch technology [25].

Resulting energy yields per hectare are expressed in biofuel equivalent, i.e. the energy contained in the biofuel that could be produced from the harvested parts per unit area. Energy requirements for crop production were not included in the calculations. Orders of magnitude and potential implications for a full energy balance are provided below along with the results.

Biofuel potentials were estimated by broad technology pathways. In each grid-cell the most productive feedstock (in biofuel energy equivalent) of 1st generation biofuel feedstocks, i.e. of oil cops, starch crops and sugar crops was selected. Similarly the best alternative of the herbaceous and woody lignocellulosic feedstocks was selected to estimate energy yields of 2nd generation feedstocks. In Europe, typical attainable (biofuel) energy yields of rainfed production range between 60 and 120 GJ ha^{-1} for 1st generation and between 100 and 180 GJ ha^{-1} for 2nd generation biofuel feedstocks, respectively (Fig. 4 and 5).

In most of Europe energy yields of oil crops are the lowest among the 1st generation feedstock groups ranging between 20 and 40% compared to those of 2nd generation feedstocks. Energy yields of 2nd generation feedstocks are systematically substantially higher than yields of 1st generation feedstocks, by some 40–80%, with the exceptions in marginal rainfed areas of Spain and dry parts of southern Ukraine, where estimated 1st generation energy yields are similar to 2nd generation feedstocks, yet at a relatively low level of around 40 GJ ha^{-1}.

Table 2 – Conversion factors from crop biomass to biofuel energy equivalent.

Biofuel feedstock group	Biofuel feedstock	Attainable yield[a] [t ha^{-1} DW[b]]	Conversion factor
1st Generation production chain			
Oil crops	Rapeseed	3–4 Seed[c]	14.4 GJ t^{-1} seed
	Sunflower	3.5–5 Seed[c]	16.2 GJ t^{-1} seed
Starchy crops	Maize	8–12 Grain	7.9 GJ t^{-1} grain
	Wheat, Triticale, Rye	6–9 Grain	7.5 GJ t^{-1} grain
Sugar crops	Sugar beet	40–70 Beet[d]	2.1 GJ t^{-1} (FW[f])
	Sweet sorghum	15–20 ABG[e]	7.2 GJ t^{-1} (DW)
2nd Generation production chain			
Woody lignocellulosic	Poplar, willow, eucalyptus	15–20 ABG	9.6 GJ t^{-1} ABG (DW)
Herbaceous lignocellulosic	Miscanthus, switch grass, canary reed	15–20 ABG	9.3 GJ t^{-1} ABG (DW)

a Indicative range.
b Dry weight.
c For oil crops an oil extraction rate of 40% of rapeseed and 44% of sunflower were assumed.
d Sugar beets and sweet sorghum (fresh weight) are assumed to contain 75% water and 15% sugar and 78% water and 10.5% sugar, respectively.
e ABG, annual above ground biomass.
f Fresh weight.

The analysis of feedstocks in terms of land use efficiency, i.e. yields expressed as biofuel equivalent per ha, within the 1st generation feedstock group indicates the relative advantage of sugar crops (especially sugar beet) for bioethanol production over oil crops for biodiesel production (Annex 4, Map 7 in [38]). Energy yields of the 2nd generation herbaceous or woody lignocellulosic feedstocks are more homogeneous.

Average energy yields vary widely between countries. Highest yielding feedstocks in each group were determined by grid-cell and aggregated by country (Fig. 6).

Energy yields for oil crops range between 26 and 57 GJ ha^{-1}; in most of Europe between 30 and 50 GJ ha^{-1}. Energy yields of the other 1st generation feedstock groups range mostly between 80 and 120 GJ ha^{-1}. The higher end of the energy yields are attributed to sugar crops, sugar beet in particular. Herbaceous and woody lignocellulosic feedstocks (2nd generation) could achieve average biofuel energy yields in most of Europe between 100 and 150 GJ ha^{-1}.

The above yields refer to gross energy yields per hectare, i.e. they do not account for the energy consumed in crop cultivation, transport and conversion. Results presented in Fig. 5 do not take into account by-products not converted to biofuels (e.g. oilcakes) and their associated energy content. The amount of energy required for producing biofuel feedstocks depends on type, agricultural management, and most significantly on level of agricultural inputs applied. The bulk of energy input comprises nitrogen fertilizer and diesel required for mechanized farm field operations. Energy requirements are in the order of 10–15 GJ ha^{-1} for cereals and oil crops [26,27], between 15 and 25 GJ ha^{-1} for sugar crops [28], 8 and 20 GJ ha^{-1} for miscanthus, and 2 and 8 GJ ha^{-1} for reed canary grass [29].

4. Discussion

Biofuel production has recently become one of the most dynamic and rapidly changing sectors of the global transport economy. Several major countries, such as the United States, China, India, and the European Union, have enacted new biofuel policies. Global production of biofuels has doubled in the last five years and is expected to double again in the next four years [30].

In 2007 the European Union consumed 7.7 Mtoe biofuels representing 2.6% of the energy content of all road transport fuels used. After four years of implementation nearly half of the 2010 target of 5.75% has been achieved. Biodiesel represented 73% of biofuels dedicated to transport, far ahead of bioethanol (16%) [6]. Rapeseed is the principal feedstock for European biodiesel production, accounting for 84% of total biofuel feedstock, followed by sunflower with 13%, which is grown in warmer climates only [31]. For the first time farmers exceeded the maximum guaranteed area for energy crop support of 2 million hectares and claimed support for approximately 2.84 million hectares of farmland. In consequence the EU has reduced the subsidy amount payable to farmers in 2007 to keep within its budget of 90 million euros [32].

This demonstrates the strong momentum biofuel production has recently gained in Europe even though up to now only relatively few countries have participated in biofuel feedstock production and consumption. While some of the envisaged increases can be achieved via imports of both biofuels and biofuel feedstocks, to meet the set target the European Union will have to increase domestic feedstock production. Sustainability of biofuel production and land competition with food and feed are central concerns for future biofuel deployment.

4.1. *Environment and sustainability of biofuel feedstock production*

Along with the 10% biofuel target the European Council agreed that the target should be binding only if production of biofuels is sustainable [4]. Sustainability criteria are currently discussed [5,33].

Sustainable biofuel production and use systems should apply equally to domestically produced as well as imported biofuels and biofuel feedstocks and include the following elements [34]:

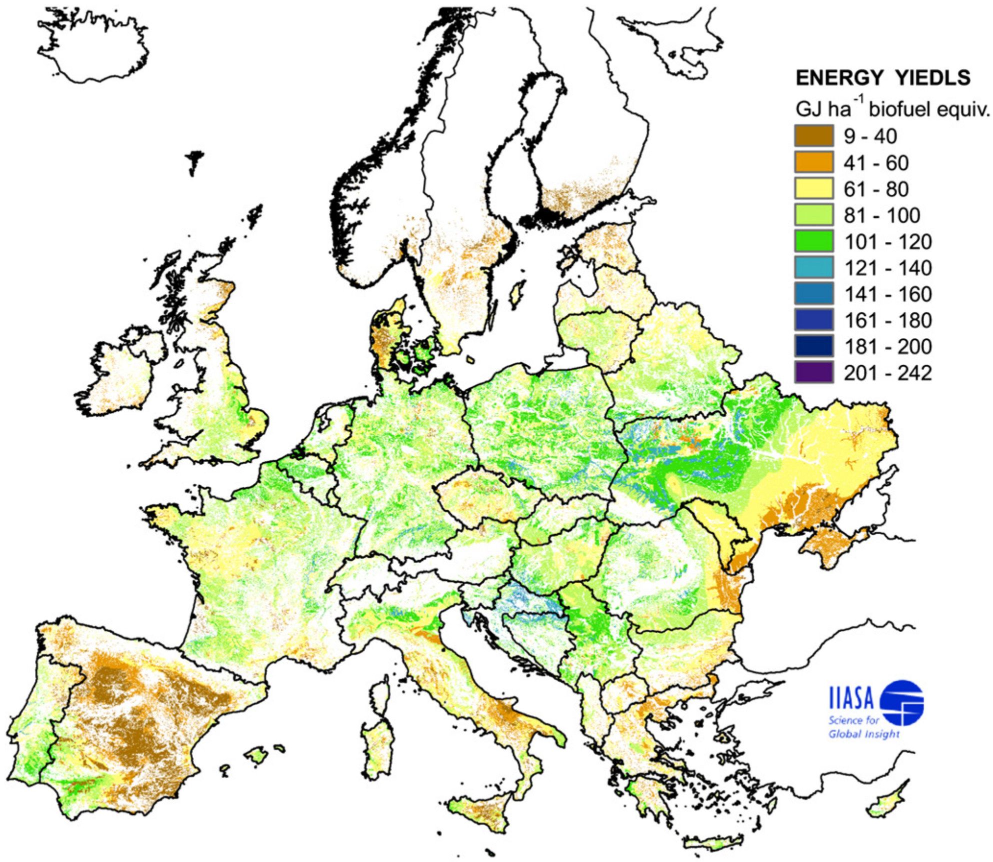

Fig. 4 – Potential energy yields of 1st generation biofuel feedstocks (cereals, sugar crops, oil crops) on cultivated land (land cover classes v–vii).

1. Considerable greenhouse gas savings (GHG) compared to the use of fossil fuels.
2. The use of environmentally sound forestry and agricultural management systems for biofuel feedstock production.
3. Preservation of landscapes with significant value for biodiversity, nature conservation, and cultural heritage.
4. Safeguard of concerns for impacts of social exclusion.
5. Integration with food, feed and other biomass use sectors reflecting societal aspirations and priorities in relation to national/regional supply and demand for energy services, food and material products – considering also the economic, security and environmental implications of supply/demand patterns.

Closely related to these sustainability requirements is the land use efficiency of biofuel feedstock production; higher energy yields per hectare reduce land requirements and may decrease land competition with food and feed production.

In the following we focus on three key issues in the biofuel discussion: GHG savings, sustainability of feedstock production systems, and land use efficiency. A fourth issue, land use competition of biofuel feedstock production with the food sector and required land use changes is discussed in a companion paper in this special issue [35].

4.1.1. *GHG savings*

One of the main reasons for advocating biofuel deployment is its stipulated environmental benefit due to reduced greenhouse gas (GHG) emissions. Assessment of GHG emission reductions resulting from the use of biofuels in the transport sector require full life cycle analysis from ‘‘from well to wheel’’. Current knowledge of GHG balances of biofuels indicates a rather large range [36].

In particular the 2nd generation production pathways can considerably reduce net greenhouse gas emissions. It has been reported that biofuels produced from certain mixtures of native grassland perennials and cultivated with low inputs of agro-chemicals, can even be carbon sinks because net ecosystem CO_2 sequestration exceeds fossil CO_2 release during biofuel production [37].

Net GHG reductions achieved for the 1st generation production pathways range in the order of 20–70%. Estimates depend on production pathways, crop types and management used [7]. Recent studies point out that 1st generation biofuels using feedstocks produced by high input agricultural production systems may even have negative GHG balances vis-à-vis fossil fuels [38]. For instance, rapeseed, Europe's main feedstock for biofuel production today, performs rather poor in its potential for GHG emission reductions due to high fertilizer and pesticide requirements for cultivation.

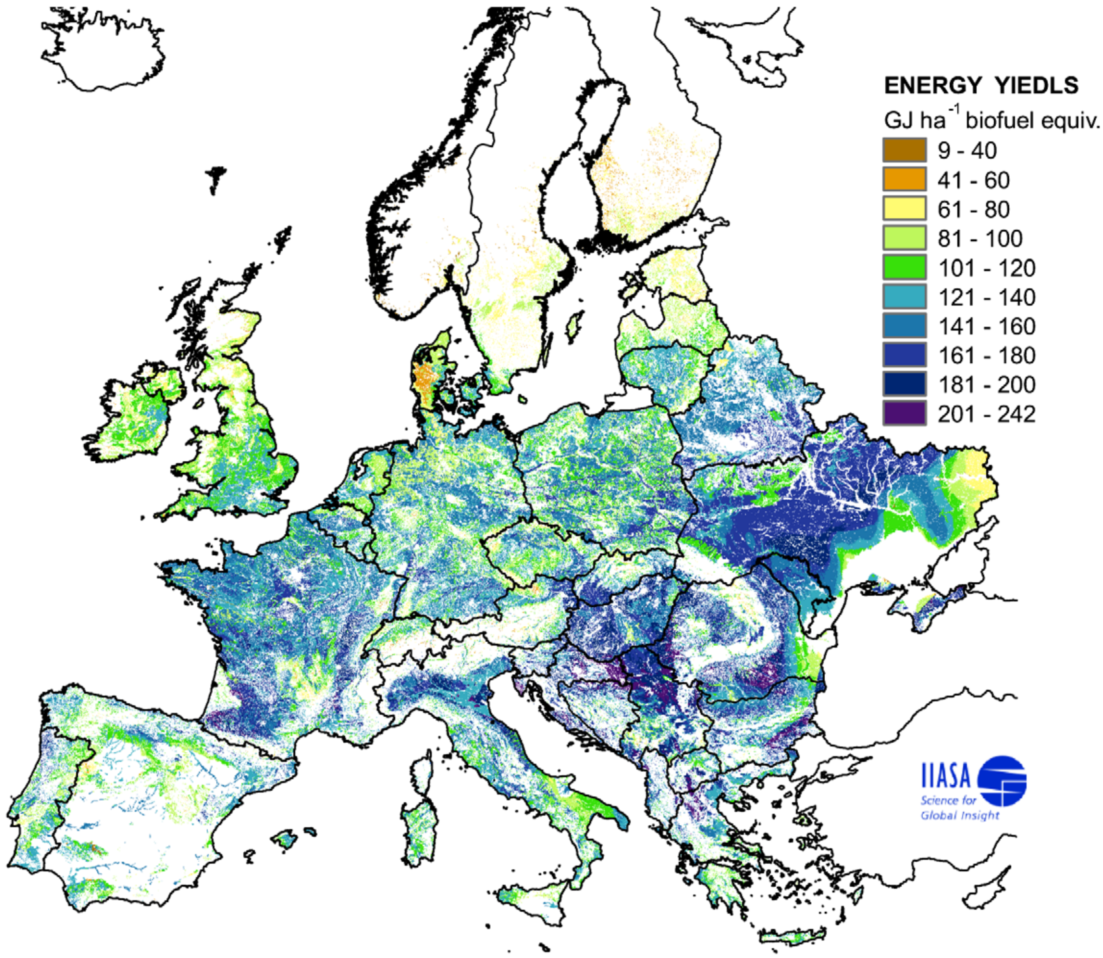

Fig. 5 – Potential energy yields of 2nd generation biofuel feedstocks on agricultural land (land cover classes v–viii).

4.1.2. *Land use efficiency*

In most of Europe the highest biofuel energy yields could be achieved with lignocellulosic feedstocks required for the 2nd generation biofuel production chains. In contrast oil crops, which dominate Europe's biofuel feedstock market today, show much lower land use efficiencies. Achievement of biofuel targets based on domestic feedstock production will require diversification of biofuel feedstock production and associated production chains.

Findings of our research highlight the substantial differences in land use efficiencies between 1st and 2nd generation biofuel feedstocks. Oil crops are typically ranging between

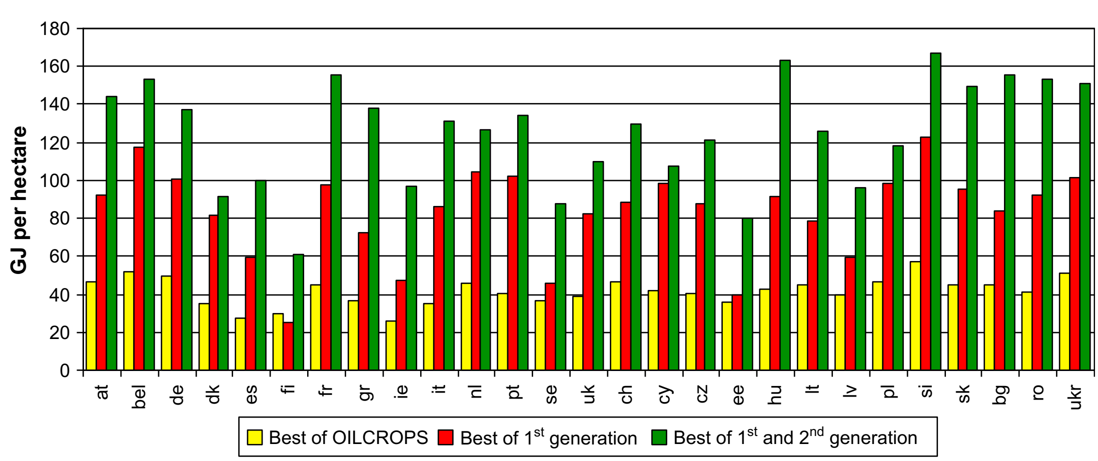

Fig. 6 – Average potential biofuel energy yields (in GJ ha^{-1}) for different feedstock groups across European countries.

20% and 40% of 2nd generation biofuel feedstock yields (Annex 4, Map 6 in [39]). Energy yields of the most efficient 1st generation feedstock compared with 2nd generation energy yields show that in large parts of Europe 1st generation feedstocks energy yields are in the order of 50–80% of yields of 2nd generation feedstocks (Annex 4, Map 5 in [39]).

Land use efficiency of 1st generation biofuels is generally highly dependent on application rates of agro-chemicals. Although appropriate management (e.g. precision-farming) may reduce negative environmental externalities of intensive agricultural production there remain severe risks of negative impacts on the environment, especially with regard to water and soil quality or preservation of biodiversity. Energy required for fertilizer and pesticide production as well as agricultural machinery for field operations lowers the amount of GHG emission reductions achievable. High land use efficiency and high GHG saving potentials may be conflicting goals, especially when considering conventional biofuel feedstocks. Further research is required to identify appropriate biofuel management schemes that optimize land use efficiency and GHG saving potentials and minimize impacts on soil and water quality and biodiversity.

Land use efficiencies of feedstocks for the 1st generation production chains may increase when utilization of co-products of biofuel production is considered. Examples include oilcakes and ‘‘Distiller's Dried Grain and Solubles’’ used as animal feed ingredient. Substitution of animal feed such as soy meal with biofuel co-products will result in less area required for soy production. Quantification of land replacement effects raises several methodological issues including treatment of joint products (e.g. soybean produces both oil for food and oilcakes for animal feed), choice and yield assumptions for the replaced commodity. In this paper no allocation of by-products has been attempted.

4.1.3. *Environmentally sound agricultural management of biofuel feedstock production*

The European Union's Common Agricultural Policy (CAP) provides the regulatory framework for biofuel feedstock production. Cross-compliance is an essential part of the reformed CAP. Cross-compliance rules ensure that in order to receive support farmers must fulfil defined rules and standards. These standards relate to the environment, public, animal and plant health, animal welfare and the sustained use of agricultural land while safeguarding the biophysical environment. CAP cross-compliance rules designed to foster environmentally sound agricultural management methods should be reviewed and adapted in view of potential increased biofuel feedstock production. Large-scale productions of biofuel feedstocks will likely trigger discussions on the use of genetically modified organism and possible conflicts should be anticipated and addressed now.

Agricultural production systems today are required to fulfil wider ecosystem functions besides the production of food, feed or energy crops. This has been included in the increasingly adopted concept of ‘multifunctional agriculture’ [40–44] the multifunctional nature of agriculture has first explicitly been recognized in the Agenda 2000 reform of the CAP [45].

Changes in emphasis of the current agricultural production systems from food and feed towards food, feed and bioenergy will require production intensification of the food and feed production systems to make room for bioenergy. Europe's spatial policies and targets are geared towards nature conversation and biodiversity (Natura 2000 describes the European Union network of sites designated by Member States under the birds directive [46] and under the habitats directive [47][1] Biodiversity Action Plan [48][2]) and clean water (Nitrates Directive [49][3]). Potential environmental pressures from the production of bioenergy feedstock in addition to intensified food and feed production need to be well-managed to ensure overall environmental benefits [9].

4.2. *First versus 2nd generation biofuel feedstocks – a farmer's perspective*

High input agricultural production systems will be required to attain economic bio-energy yields for the 1st generation technology production chain (oil crops, starch crops, sugar crops). Potential negative environmental impacts due to high fertilizer and pesticide will require careful management including adoption of precision-farming techniques.

Bioenergy feedstocks of the 2nd generation technology chains permit relatively high-energy yields with modest use of agro-chemicals and low tillage intensities. These feedstocks and in particular some perennial grasses are compatible with ecological agriculture [50].

While 1st generation biofuel technologies have reached an advanced stage and are widely used in many countries, 2nd generation technologies are still mainly applied in experimentation and demonstration projects. To prepare for the large-scale use of cost-competitive 2nd generation biofuels, continued research and development is needed. Significant changes in farm management and supply infrastructure are necessary to successfully introduce a bioenergy economy based on 2nd generation conversion technologies.

The rapid deployment of 1st generation feedstocks in Europe in the past few years reflects favorable adoption rates of the agricultural sector to feedstock production for 1st generation conversions. For this, farm technology required minor adaptations – farmers could easily integrate energy crops into their food and feed crop rotation patterns – and decentralized production, both in terms of industry and feedstocks has been proven feasible. Small farms participating in the market with relatively low investments could benefit from earnings of bioenergy feedstock production (mainly rapeseed and sunflower). An additional potential benefit refers to the use of valued by-products of 1st generation biofuel technologies, e.g. oilcakes as a by-product of biodiesel production. Yet, large-scale 1st biofuel production may substantially impact on other commodity markets such as glycerol or other products of the oleochemical industry. These side effects require further analysis.

[1] Natura 2000 describes the European Union network of sites designated by Member States under the birds directive and under the habitats directive.

[2] The European Community biodiversity strategy (COM(1998) 42 final) and its action plans set out the framework for developing Community policies and instruments in order to ensure Community compliance with commitments given under the Convention on Biological Diversity.

[3] Directive 91/676/EEC.

A key challenge for the 2nd generation technology chain is to develop conversion technologies at industrial scale at competitive prices. These technologies require large-scale feedstock supplies with associated challenges for logistics and management. At the farm level more fundamental and partly difficult to reverse land use changes will be inevitable. Farmers may only be willing to consider 2nd generation herbaceous and fast growing woody species when a stable and sustained demand for 2nd generation feedstocks is proven. Farmers need to do (i) substantial investment in adapted farm technology, (incl. farm machinery and infrastructure), (ii) are required to modify planning horizon, and (iii) may face high cost to return the conventional annual cropping systems.

In Europe, experience and relevant field-scale data on management techniques of the production of lignocellulosic feedstocks is limited. Additional research is required for optimizing management of lignocellulosic energy crops for the diverse biophysical conditions across Europe. Experience of European farmers with energy crop plantations is very limited, and transition to lignocellulosic feedstock systems requires tailor-made agricultural extension services assisting farmers on the various aspects of production from planting to harvesting.

5. Conclusions

This study presents a database for agricultural biofuel feedstocks throughout Europe at a spatial resolution of 1 km^2. Main findings relate to energy yields, land use efficiency, the debate on 1st versus 2nd generation feedstocks and sustainability of feedstock production.

Energy yields and land use efficiency vary by conversion pathway, feedstock and location: The analysis highlights the importance of the *spatial variation* of energy yields depending on feedstock type and biophysical conditions and provide a basis for assessing the location-specific comparative advantages of specific biofuel feedstocks. Findings highlight substantial differences in land use efficiencies, i.e. yields expressed as biofuel equivalent per hectare, between the various biofuel feedstocks groups. Average energy yields vary widely between countries.

- Typical attainable (biofuel) energy yields of rainfed production range between 60 and 120 GJ ha^{-1} for 1st generation. Energy yields of herbaceous and woody lignocellulosic 2nd generation feedstocks are substantially higher than those of 1st generation feedstocks, by some 40–80%, achieving mostly between 100 and 150 GJ ha^{-1}. Exceptions are in marginal rainfed areas of Spain and dry parts of southern Ukraine, where estimated 1st generation energy yields are similar to 2nd generation feedstocks, yet at relatively low levels of around 40 GJ ha^{-1}.
- Energy yields of oil crops are the lowest among the 1st generation feedstock groups ranging between only 20 and 40% compared to those of 2nd generation feedstocks (excluding by-products).
- Land use efficiency of 1st generation biofuels is generally highly dependent on application rates of agro-chemicals. Intensive agricultural production in general poses severe risks of negative impacts on the environment, especially with regard to water and soil quality or preservation of biodiversity. Appropriate management (e.g. precision-farming) may reduce negative environmental externalities.

First versus Second generation biofuel feedstocks: while 1st generation biofuel technologies have reached an advanced stage and are widely used in many countries, 2nd generation technologies are still mainly applied in experimentation and demonstration projects.

- A key challenge for the 2nd generation biofuels is to develop conversion technologies at industrial scale at competitive prices. These technologies require large-scale feedstock supplies with associated challenges for logistics and management.
- Farmers (i) need to do substantial investment in adapted farm technology, (incl. farm machinery and infrastructure), (ii) are required to modify planning horizon towards the longer-term, and (iii) may have to give up flexibility by facing potentially high costs when returning to conventional annual cropping systems.
- Experience of European farmers with energy crop plantations is very limited, and transition to lignocellulosic feedstock systems requires tailor-made agricultural extension services assisting farmers on the various aspects of production from planting to harvesting.

Sustainability of feedstock production: agricultural production systems today are required to fulfil wider ecosystem functions besides the production of food, feed or energy crops.

- Changes in emphasis of the current agricultural production systems from food and feed towards food, feed and biofuel will require production intensification of the food and feed production systems to make room for biofuel.
- Europe's spatial policies and targets are geared towards nature conservation and biodiversity. Potential environmental pressures from the production of biofuel feedstock in addition to intensified food and feed production need to be well-managed to ensure overall environmental benefits.

Suggested further research:

- As long-distance inland transport of bulky lignocellulosic feedstocks would be un-economic, the spatial database can also support locating new biofuel industries while considering large and continuous feedstock demand.
- Climate change may affect biomass and energy potentials in some areas. The use of climatic change scenarios could add an additional dimension to the analysis with regard to the long-term viability and stability of feedstock biomass yields.
- Large-scale productions of biofuel feedstocks will likely trigger discussions on the use of genetically modified organism and possible conflicts should be anticipated and addressed.

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