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EU Framework Program for Research and Innovation actions (H2020 LCE-21-2015)

MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

Annex 10: Task 2.2.e.4 Land uses due to the transition to a low-carbon economy

Version 2.0.0

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WP: WP2, Data collection

Task: Annex 10: Task 2.2.e.4. Land-uses due to the transition to a low-carbon economy

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Table of contents

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Scope of document

The global aim of MEDEAS project is to provide policy makers and stakeholders with a new tool, to better assess the impacts and limitations of the EU energy production/consumption system transition to a low-carbon sustainable socio-economy. This tool will integrate energy, raw materials supply and socioeconomic behavior in an energy systems simulation model.

Specifically, Deliverable 2.2 is focused on providing the necessary analyses in selected sectors that need to be carried out in order to run the model properly: (1) Electricity sector; (2) Transportation; (3) Total primary energy extraction; (4) Industry, residential and commercial energy requirements; and (5) social welfare and environmental impacts indicators analysis. This Annex documents the impacts in terms of land-use due to the transition to a low-carbon economy from the 5th sector. First, the trends and drivers of land-use change at global and EU-level are reviewed: urbanization, increasing demand & dietary change, energy and conservation policies. Secondly, the environmental impacts of land-use change are assessed in terms of land-use greenhouse gas emissions, deforestation and biodiversity loss. Finally, we discuss the integration of land-use in the MEDEAS framework.

It should be noted that this is a living document and that the suggested analyses will constitute a starting point for MEDEAS Model. Additional analyses might be required and some might be abandoned as the project proceeds and if new requirements are detected.

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List of abbreviations and acronyms

AFOLU: Agriculture, forestry and other land-use

CCS: Carbon capture and storage

CSP: Concentrating solar power

EJ: Exajoule

EROI: Energy return on energy invested

EU: European Union

GCAM: Global Change Assessment Model

GHG: Greenhouse gases

GIS: Geographic information system

IAM: Integrated Assessment Model

ILUC: Indirect land-use change

IMAGE: Integrated Model to Assess the Global Environment

LCA: Life-cycle analysis

Mha: Megahectares

PV: Photovoltaic

RES: Renewable energy sources

US: United States of America

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Executive summary

Land is a critical component of any analysis focusing on sustainability and its consideration qualitatively modifies the results obtained by energy-economy-environment models. Thus, Land is one of the main modules of MEDEAS together with Economy and Population, Energy, Climate, Materials and Social. MEDEAS will generate demand trends of different energy technologies that will be dynamically matched with the supply availability (i.e. materials, infrastructure deployment rhythms (i.e. time), etc.) being land availability one of them. The Land module in MEDEAS will be directly linked with -at least- three other modules: Economy and Population (e.g. through food and services demand), Energy (e.g. through energy policies, i.e. land requirements of different energy mixes) and Climate (e.g. through land-use change CO_2 emissions). This module will cover two main objectives: (1) assess the potential restrictions that land availability might impose to RES deployment (mainly bioenergy, solar and pumped hydro), and (2) estimate the land-use change GHG emissions to feed the climate model.

The literature review shows that the main drivers of land-use will continue to operate in the next decades at both global and European level: population growth, urbanization trends and shift to more land-intensive diets. Moreover, additional factors will likely arise in the next decades as a result of the promotion of renewable energies and climate policies. The dedication of land to produce energy has been identified as a potential concern not only for preserving natural ecosystems, their services and biodiversity, but also because of its competition with land use to cover human needs (i.e., food, fiber, shelter and infrastructure) given their lower surface power density. Thus, the transition to a low carbon economy could aggravate existing vulnerabilities and create new ones in terms of energy security, biodiversity loss, and food sovereignty, among others. Given that the future availability of technological ways to sequestrate carbon (such as carbon capture and storage CCS) is subject to many uncertainties and may even not be available at the large scale required, afforestation and soil-management emerge as key strategies to store carbon. Especially relevant for the European model is the fact that the EU is particularly vulnerable to future developments given its current high dependence on foreign land to cover its consumption of goods and services. The EU uses for its consumption about 1.5 times its own territorial land use abroad, mainly in Latin America and Africa.

First of all, the relationship between the drivers and the impacts of the variables of the Economy and Land submodules at both global and European level should be modelled. Databases such as FAOSTAT and EUROSTAT will be the main base for the extraction of data. In relation to the

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estimation of land-use change emissions, other IAMs that consider Land-use system such as GCAM and IMAGE could be taken as reference. Subsequently, projections of future food requirements (including diets), urbanization and infrastructures expansion, degraded land, required land for preserving biodiversity should be built in a scenario methodology framework. These projections will be challenged by the fact that they are affected by other modules of MEDEAS. For example, degraded land and biodiversity conservation trends will be critically affected in the future by the level of global environmental change. The energy mix will drive the land requirements for energy production (mainly bioenergy and solar). Given that substantial levels of both food and energy (mainly in the form of biomass) can be imported, assumptions about energy and food security should be made for the regional modeling of Europe within the global model. Other variables as water may be important for the robustness of the land-module given the dependency of crops (and some energy technologies) on the availability of this resource.

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1. Introduction

Anthropogenic land-use activities (e.g., management of croplands, forests, grasslands, wetlands), and changes in land use/cover (e.g., conversion of forest lands and grasslands to cropland and pasture, afforestation) are a critical component of sustainability and as such it has been identified as one of the planetary boundaries of the biosphere. A planetary boundary refers to a specific point related to a global-scale environmental process beyond which humanity should not go if disastrous consequences are to be prevented (Steffen et al., 2015). Since land-use has a strong regional operating scale the transgression of its boundary at the regional level affects the Earth System at the global level:

> *The updated biosphere integrity boundary provides a significant constraint on the amount and pattern of land-system change in all terrestrial biomes—forests, woodlands, savannas, grasslands, shrublands, tundra, etc. The land-system change boundary is now focused more tightly on a specific constraint: the biogeophysical processes in land systems that directly regulate climate—exchange of energy, water and momentum between the land surface and the atmosphere. The control variable has been changed from the amount of cropland to the amount of forest cover remaining, as the three major forest biomes—tropical, temperate and boreal—play a stronger role in land surface-climate coupling than other biomes (56, 57). […]*
>
> *Of the forest biomes, tropical forests have significant feedbacks to climate via changes in evapotranspiration when they are converted to non-forested systems, while changes in the distribution of boreal forests affect the albedo of the land surface and hence regional energy exchange. Both have strong regional and global teleconnections* (Steffen et al., 2015).

Several indicators suggest that current land-use is unsustainable. Steffen et al., (2015) found that the land-use/cover change in natural ecosystems has surpassed its planetary boundary and currently lies in the zone of uncertainty and increasing risk. The human appropriation of net primary production, i.e. the human alterations of photosynthetic production in land ecosystems and the harvesting of products of photosynthesis, is around 25% (10-55%) of the global total (Vitousek et al 1986, Rojstazcer et al 2001, Krausmann et al . 2013, Haberl et al., 2007). The global Ecological Footprint surpassed the global biocapacity ratio in the 1970s, which since then is being depleted (the global ecological footprint is assessed at over 150%) (GFN, 2015), etc. Land-use emissions (agriculture, forestry and other land-use, i.e. AFOLU) are the second cause globally after

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the energy supply sector, with an estimated contribution of 24% in 2010, and above other uses such as transport (IPCC, 2014).

The global competition for land is driven by many factors, such as increasing affluence, population growth, energy policy, dietary preferences, protected areas management or international trade regulations. Thus, future policy decisions in the agriculture, forestry, energy and conservation sectors as well as societal changes (e.g. diets) will have profound effects, with different demands for land, to supply multiple ecosystem services usually intensifying competition for land in the future (Kastner et al., 2012; Rulli et al., 2013; Scheidel and Sorman, 2012; Smith et al., 2010; Weinzettel et al., 2013).

Furthermore, climate policy will need also to include land for designing consistent greenhouse gases (GHG) mitigation policies given that substantial levels of carbon sequestration will be required to stabilize the global climate (González-Eguino et al., 2016; Hansen et al., 2016; IPCC, 2014; Otto et al., 2015).

In particular, the European Union (EU) is highly dependent on land outside its territory to cover its needs. In 2008, the share of the land footprint covered with domestic land use (i.e. the land footprint coverage ratio) was 45% in the EU-27, down from 47% in 1995 (Arto et al., 2012), with other analysis finding it to be around 40% (Tukker et al., 2016) (see Appendix 1).

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2. Methodology

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2.1. Trends and drivers of land-use change

In this section the main trends and drivers of land-use change are reviewed: expansion of urbanized areas, the increasing food demand and dietary change, and the energy and conservation policy.

2.1.1.Expansion of urbanized areas

Human infrastructures currently occupy between 1 and 2% of total terrestrial land. For some dense populated countries, this share can surpass 5% of their territories, mainly in temperate climatic zones. However, in high mountains, hot and cold deserts and tropical forested zones, human density population are much lower and therefore human infrastructure densities follow. The EU-average is 3.5%, with large variations between member states: e.g. Ireland and Spain (1.8-2%), Germany (7.6%) and Netherlands and Belgium (13-14%) (Capellán-Pérez et al., 2016; FAO/IIASA, 2011).

The projected increase in affluence and growth of human population will foster the demand of land for settlement and infrastructures in the next decades, requiring substantial levels of energy, materials and capital. Although present direct land occupation, mostly in suitable areas for human settlement and infrastructures, is roughly 200-400MHa (Wackernagel et al., 2002; WWF, 2008; Young, 1999), more than 75% of the Earth's ice-free land (i.e. > 10,000MHa) is altered as a result of human settlements and other land uses (Ellis and Ramankutty, 2008).

The projected growth of new infrastructures because of population and affluence growth is more than 100MHa for the next decades (Schade and Pimentel, 2010; Young, 1999).

2.1.3. Increasing food demand & dietary change

Agricultural land occupies around 4,900 MHa (1,535 MHa for cultivated area and 3,364 MHa for meadows and pastures) of a global land ice-free of around 13,000MHa (FAO Stats, 2013).

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Global agricultural production has increased more than 150% over the past five decades. The rate of output growth has remained remarkably consistent over the past 50 years— averaging 2.7 percent per year in the 1960s and between 2.1 and 2.5 percent per year every decade since. Over this period, the high rate of growth in production levels occurred primarily through yield growth (from inputs such as fertilizers, energy, water and capital equipment) rather than cropland expansion (Sands et al., 2014). Yet, these yield improvements were not able to compensate for the increasing demand of food : from 1961 through 2009, the world's cultivated area grew by 12%. However, today, approximately a billion people are chronically malnourished (Foley et al., 2011).

Organic agriculture use only 37,2 MHa in 2011 but with a strong increase in the last years (11 MHa in 1999).

Although global yields for maize, rice, and wheat grew rapidly from 1961 to 2007, for all those crops, in both developed and developing countries, rates of yield growth were slower during 1990 to 2007 than during 1961 to 1990 (Figure 1). A slowdown in crop yield growth was seen in more than half of the countries that grew the three crops. More critically, compared with all producing countries, a higher proportion of the top 10 producing countries experienced a slowdown for all three crops. Thus, yields might be approaching biophysical limits in many regions. A hypothesis that can explain the occurrence of yield plateaus is that average farm yields approach a biophysical yield ceiling for the crop in question, which is determined by its yield potential in the regions where the crop is produced. In any case, this slow-down of yield improvements has contributed to the increase of the recent expansion of agricultural land from 2002 in advance (average 9,8 MHa/yr increase, against 5,3 MHa/yr for 1965-1982 and 1,6 MHa for 1982-2001) in order to meet food demand growth (Alston et al., 2009; Grassini et al., 2013).

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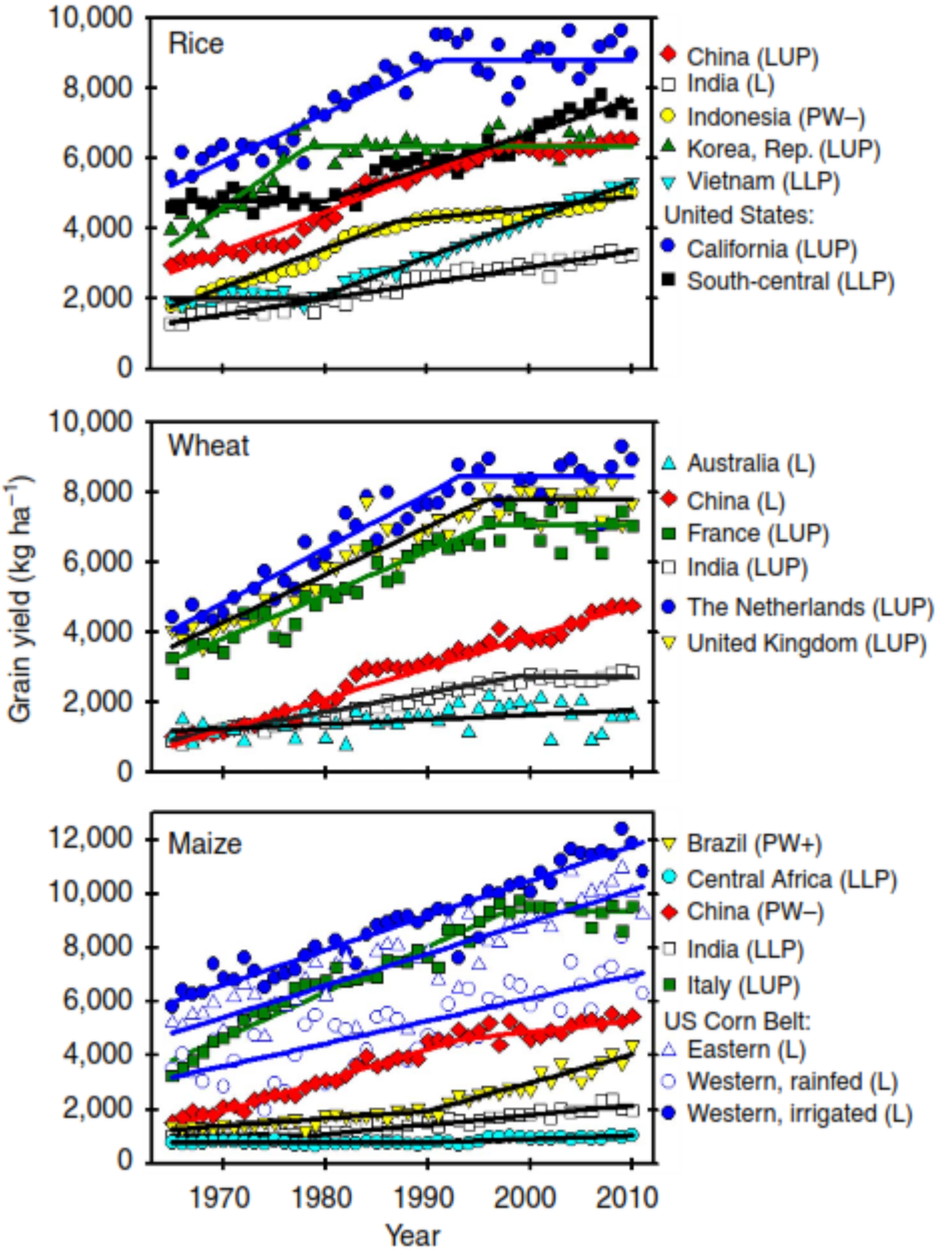

Figure 1 (Grassini et al., 2013): Trends in grain yield of the three major cereal crops for selected regions since the start of the green revolution in the 1960s.

In fact, forecasts on yield productivity growth have been frequently exaggerated, and exponential forecasts of yield productivity (constant annual growth rate) therefore are not justified by past decades trends (Grassini et al., 2013) (see Figure 2).

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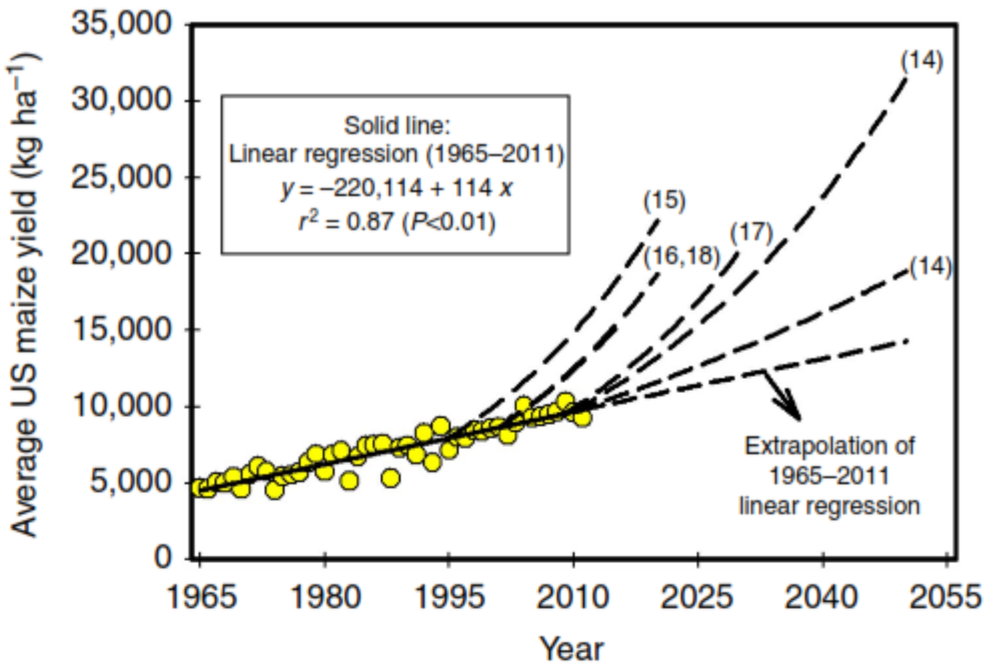

Figure 2 (Grassini et al., 2013): Historical trend in average US maize yield and reported projected trajectories based on compound rates of yield grain.

It is expected that the projected increase in affluence and growth of human population will foster the demand of land for food production in the next decades. The foreseeable growth of land for food for the next few decades is projected to be 200-750MHa (Balmford et al., 2005; FAO, 2003; Rockström et al., 2007; Schade and Pimentel, 2010), but the new land that we could convert to agriculture is 300-500MHa (Schade and Pimentel, 2010), or 386MHa in a sustainable way, converting abandoned agricultural land (Campbell et al., 2008; Rockström et al., 2009). This means that it may be not possible to meet the current trends of demand for food if the degraded land continues to grow, as more than 350MHa will be lost if present trends continue (Foley et al., 2005; Pimentel, 2006).

Moreover, a change to more affluent diets including higher meat and dairy consumption results in the need to expand or intensify agricultural and forestry production. The additional inputs required to intensify production, including fossil energy, nitrogen, phosphorus, and fresh water, are themselves in limited supply and their use leads to ecosystem impacts (Weinzettel et al., 2013). In fact, in the past, land savings through yield increases were offset by a combination of population growth and dietary change. Among the food categories accounting for increasing land demand, animal products are the most important ones, representing almost half the additional

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cropland requirements since the 1960s (Kastner et al., 2012). In fact, ~70-75% of agricultural land is currently devoted to raising animals (FAO 2013, Foley et al., 2011). In this sense, diets change are often proposed as a sustainable policy in order to reduce land-use and associated environmental impacts while reaching healthier diets (e.g. (Billen et al., 2015; Foley et al., 2011; Green et al., 2015)).

In Europe, around 30% of the land is currently dedicated to agriculture (Capellán-Pérez et al., 2016; FAO/IIASA, 2011). Europe is particularly affected by the potential proximity of yields plateaus, especially for countries such as United Kingdom, France, Germany, The Netherlands, Denmark, Italy and France (Grassini et al., 2013). Thus, in the absence of substantial dietary shifts or changes in the food import-export structure of Europe, it is unlikely that the are dedicated to agriculture will decrease in the next decades.

2.1.4. Energy policy

While fossil fuels represent concentrated deposits of energy and thus can be exploited at high power rates (200-11,000 W_e/m^2, (Smil, 2015)), the technologies harnessing renewable sources are characterized by power densities several orders of magnitude lower. That means that, for delivering the same power, renewable energies are substantially more land intensive. For example, typical ranges of net power density found in the literature are: 2-10 W_e/m^2 for solar power plants, 0.5-7 W_e/m^2 for large hydroelectric, 0.5-2 W_e/m^2 for wind; and below 0.1 W_e/m^2 for biomass (de Castro et al., 2014; MacKay, 2013; Miller et al., 2015; Miller and Kleidon, 2016; Smil, 2015). While wind farms are partially compatible with other uses (e.g., agriculture) or can be located offshore, biomass plantations, hydroelectric reservoirs and solar farms tend not to allow double use, that is, in practice they monopolize the occupied land. In the case of solar power, the potential in urbanized areas is limited due to the fact that cities are currently not designed to maximize solar reception (Izquierdo et al., 2011; La Gennusa et al., 2011; Ordóñez et al., 2010; Sorensen, 1999).

Hence, the transition to renewable energies will add to the pressure in the global competition for land (Capellán-Pérez et al., 2016; Scheidel and Sorman, 2012; Smith et al., 2010). However, few studies have focused to date on the quantitative analysis of its implications. There is an ongoing discussion where most of the studies focusing on 100% RES scenarios estimate that the additional land requirements. There is an ongoing discussion in relation to the land implications of the transition to RES, with some authors arguing that they dowill not be a compelling constraint for the transition are manageable by the current socio-economic system(e.g., Jacobson and Delucchi (2011), WWF (2011), Jacobson et al., (2015), Teske et al., (2015) and García-Olivares (2016)). In

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fact, considering the intermittencies and seting aside unrealistic scenarios of vast intercontinental transfers of electricity, the land-use implications of the transition to RESfor many countries are significant (Capellán-Pérez et al., 2016; MacKay, 2013; Wagner, 2014).

Different definitions of energy potential exist. The technical potential takes into account, for instance, the energy that the windmills or panels can extract, considering current or future plausible technological efficiencies. Economic potential and sustainable potential are the fractions of the technical potential considering, respectively, the restrictions derived from the costs of the technologies and the constraints derived from sustainability and ecosystem damage criteria (see for instance (de Vries et al., 2007)).

Figure 3 shows the potentials for solar (PV and CSP) and wind (onshore and offshore) obtained by a study accounting for limitations such as land-use competition and acceptance, together with resource quality and remoteness as proxies for cost (Deng et al., 2015).

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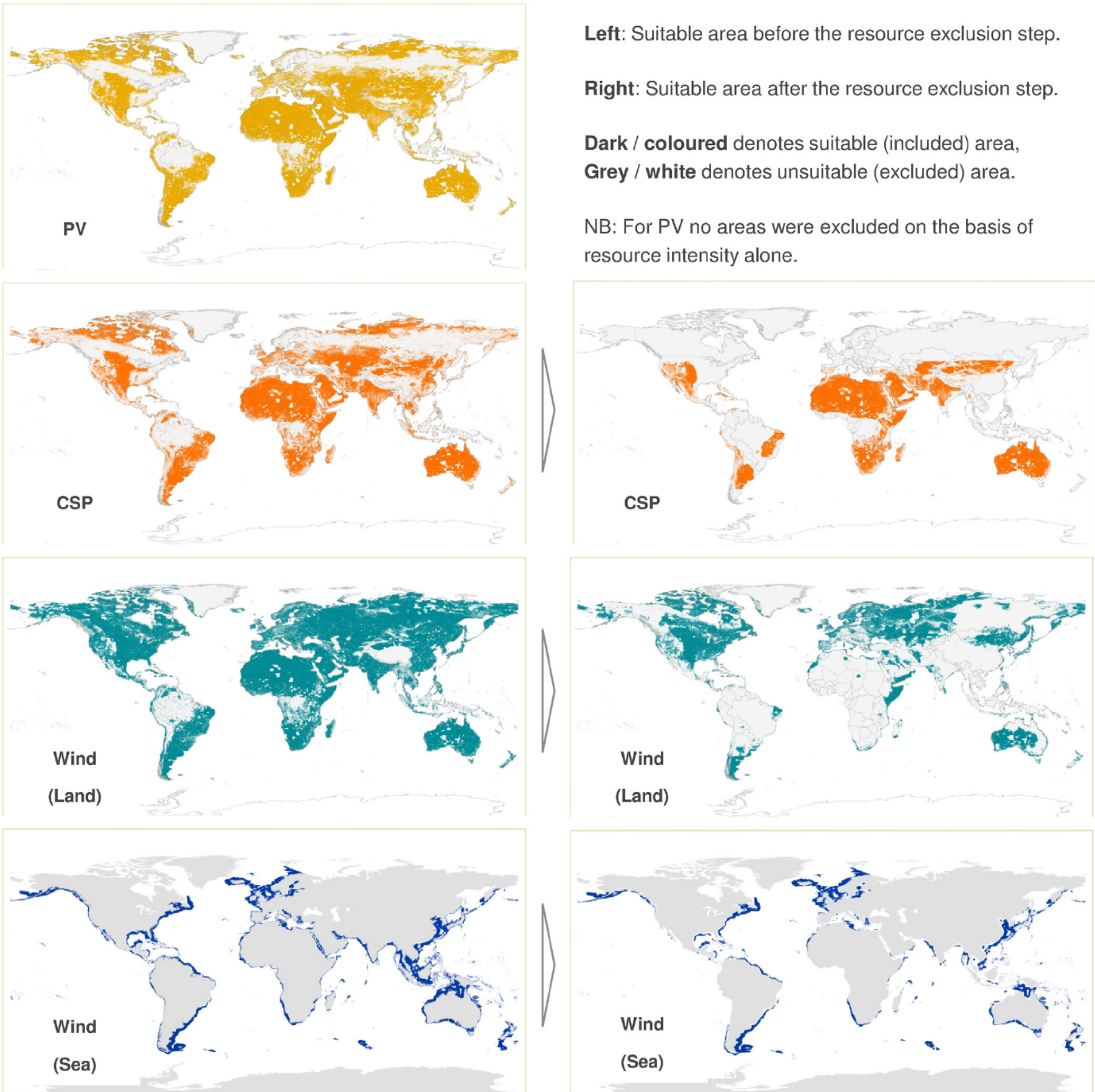

Figure 3 (Deng et al., 2015): Suitable area by technology estimated by (Deng et al., 2015). The suitable area on land and sea is found by successive exclusions for technical and economic reasons, using the resource intensity as a marker for economic viability. The figure shows available area before (left) and after (right) the resource exclusion step. From top to bottom: PV on land, CSP on land, Wind on land, Wind on sea. Dark/coloured denotes suitable area, grey/white denotes excluded area.

For the case of the EU, solar potential is generally low (excepting in the southern countries close to the Mediterranean Sea), wind potential being generally higher (especially in the north and in the ocean platform).

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2.1.4.1. Bioenergy

Biomass total primary energy demand was 58,5 EJ in 2014 (around 10% of the total) with 54% to 60% from traditional biomass for heating in household energy consumption in developing countries of Asia and Africa (REN21, 2015).

As of 2,5 billon people rely on traditional biomass (fuelwood, charcoal, agricultural waste, animal dung) that has lesser efficiencies than modern biomass for heating (biogas, pellets, municipal waste…), pressure over forest and agricultural land continues growing although it is very difficult to estimate the land necessities or changes due to this source of energy (REN21, 2015).

Biomass for heat accounts for 77% of total biomass primary energy demand and 30% is generated from modern biomass (around 13,5 EJ) (REN21, 2015).

Biopower (electricity) production is 1,6 EJ (REN21, 2015) and has similar land necessities than biofuels per net Joule delivered to society if it is not provided by waste or deforestation (de Castro et al., 2014).

Present occupation of land for biofuels is roughly 60-100 MHa[2] (in 2008 the occupation was estimated at 36 MHa with annual growth well over 10% (UNEP, 2009), in 2010 was estimated at around 45 MHa (FAO Stats, 2013), with an output of over 3 EJ in 2015 (BP, 2016). Future assessments range 50MHa for 2030 to more than 1,500 MHa for 2050 (UNEP, 2009).

Biofuels and bioelectricity form crops have a very low net energy density (less than 0,07 W/m^2), have an Ecological Footprint greater than fossil fuel resources, have similar or greater emissions of GHG that fossil fuel derived sources, are a source of soil erosion and water depletion and in conclusion could be regarded as a non-renewable, non-sustainable energy sources (de Castro et al., 2014; Pimentel et al., 2009; Searchinger et al., 2008).

The EU has intensively promoted biofuels since 2000, reaching 5-6% of liquids consumption. However, the target of 10% of energy in transport coming from 1st generation biofuels in each Member State by 2020 was suspended due to the environmental and social consequences of their use on such a large scale. In fact, there has been a trade-off between energy and food security in EU: although in the first years of promotion biofuel consumption was mainly covered by EU-

[2] The bottom-up methodology using the production per hectare used by UNEP (2009) has been shown to be conservative in terms of land requirements (see (de Castro et al., 2014) for details). For the 2008 data the gross energy biofuel production was 1,75EJ or 0,155W/m^2

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production, from 2006 onwards the imports have risen considerably (ICCT, 2013) (see Figure 4) since the land availability in EU is limited. In fact, according to OECD estimates in 2006 the EU-15 would require over 70% of its crop area to replace 10% of its transport fuel consumption by biofuels (OECD, 2006).

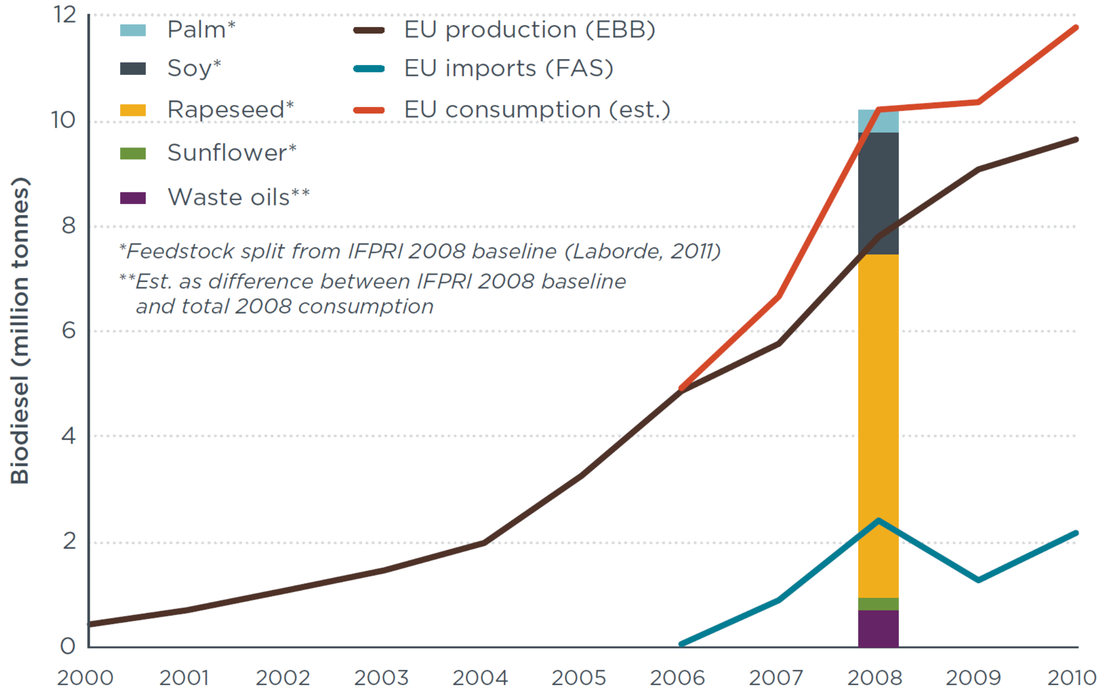

Figure 4 (ICCT, 2013): EU biodiesel production, imports and consumption 2000-2010, with 2008 feedstock mix.

2.1.4.2. Solar

2.1.4.2.1. PV on buildings and in urban areas

Studies that evaluate this potential at a regional or country level are very common in the literature (e.g., (Bergamasco and Asinari, 2011; Byrne et al., 2015; Izquierdo et al., 2011; Jo and Otanicar, 2011; La Gennusa et al., 2011; Ordóñez et al., 2010; Paidipati et al., 2008; Wiginton et al., 2010)). Despite the potential being substantially reduced when considering shading, orientation, and other availability factors, it is generally found that rooftop PV could cover from a very low to moderate share of the electricity consumption. However, there is a substantial lack of standardization and no consensus method exists in the literature, with different methodologies

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achieving a different geographical coverage and different levels of spatial resolution (Melius et al., 2013). Hence, global estimates based on a consistent methodology across regions are scarce. In general GIS-based methods represent a more objective and accurate approach for identifying rooftop availability than others based on constant values (Mainzer et al., 2014; Melius et al., 2013).

It has been estimated that it would only be possible to cover a small percentage of today's urban areas with solar panels (<2%), assuming acceptable efficiency (La Gennusa et al., 2011; Sorensen, 1999), since existing urban and architectural designs were not conceived to incorporate solar modules and are poorly compatible with them. Ordóñez et al. (2010) performed an extensive GIS-based analysis for all the urbanized areas in Andalusia (Spain) taking into account the maximum occupation of roofs (9.4% of the urbanized area; Instituto de Estadísticas de Andalucía (2015)). Without taking into account non-usable buildings (e.g., heritage protection) or shadows between buildings (personal communication), they found a potential of 3% of surface area covered in relation to the urbanized land in that region. Thus, in current conditions, a plausible maximum range dedicated to PV systems would be in the order of 2-3% of the urban area.

However, in practice, there are other uses for rooftops: daylighting, solar thermal, roof-top gardens or terraces, etc. Although some uses might be compatible with rooftop PV (and sometimes even complementary, e.g., green roofs, hybrid solar collector, etc.), others will compete for the available roof space, some of these uses already being promoted as sustainable/green practices. For example, solar thermal is a promoted and competitive technology already occupying many suitable locations (Cansino et al., 2011; REN21, 2015) (including high latitude regions (Hagos et al., 2014)), and needs to be close to consumers due to the technical difficulty of transporting heat over large distances without incurring in high losses, unlike electricity (IEA, 2006). Globally, solar thermal already accounts for about 1.2% of water and space heating in buildings (REN21, 2015).

Considering a 1-2% range availability, (Capellán-Pérez et al., 2016) found that rooftop PV could cover the following shares of current electricity use (excepting hydroelectricity production) for the following countries: Japan (1.4-4.7%), Denmark (1.6-5.5%), Spain (2.4-8.1%), Mexico (8.9-29.6%).

2.1.4.2.2. Potential of solar technologies on land

Following the assessment of the previous section, important shares of solar energy will require to be installed on land in order to cover current consumption levels.

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A recent work reviewed the impacts on biodiversity, land-use and land-cover change, soils, water resources, and human health of solar on land (Hernandez et al., 2014). In particular, the expansion of solar, even reaching low penetration levels, has already proven to have the potential to substantially contribute to additional land competition, e.g. in California (Hernandez et al., 2015) or Italy. In the latter, with solar covering roughly 5% of the electricity consumption of the country, there was a controversy in the country in relation to land requirements (corresponding to ~0.1% of Italian agricultural surface area) that the legislators banned national incentives granted by the feed in-scheme to PV systems installed on agricultural soil (Squatrito et al., 2014).

Electricity generation from solar are dependent on the irradiance of the location and the technology considered, being PV power plants the most efficient in terms of land-use, i.e. achieving the highest power density. De Castro et al (2013) estimates, based on real examples, the present and foreseeable future density power of solar infrastructures at global level (3.3 and 5 W/m2, respectively). The obtained values are between 4 and 10 times lower than most published studies since most studies apply idealized assumptions about efficiency and land-occupation ratios (a more refined study focusing on 40 countries found the following likely future ranges: e.g. Spain (4.0-6.6 W/m2), USA (3.6–6 W/m2), Germany (2.6-4.4 W/m2), UK (1.8-3.0 W/m2) (Capellán-Pérez et al., 2016)).

When applying the real density power of solar infrastructures as estimated by de Castro et al (2013) to the estimated solar power potential in the literature, the land requirements sky-rocket (see Figure 5). Blue columns refer to the land necessities in the literature, which can be compared to the land dedicated for agriculture today (~1,500 MHa, in green).

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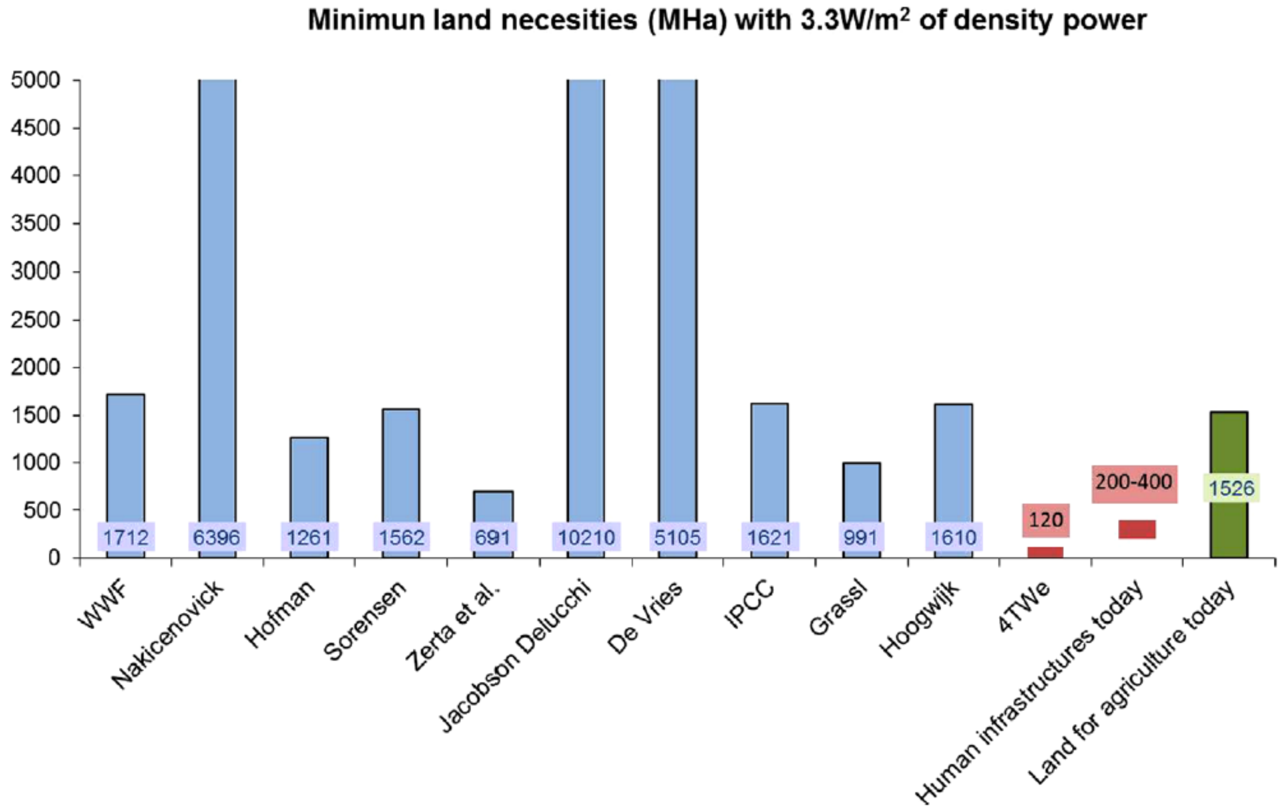

Figure 5 (de Castro et al., 2013): Minimum land requirements with the estimated power density by (de Castro et al., 2013) (3.3We/m2) to reach the technical potentials in the literature (blue columns).For comparison, the land requirements for a net power production of 4TWe (red column), the approximate current area occupied by human settlements and infrastructures (red bar) and the land currently dedicated to agriculture (green column), are also represented.

GIS-based studies allow to analyse the potential land available for solar technologies. A study focusing on South Carolina (USA) found that just a 0,08% of the territory might be used for solar technologies avoiding competition with current agricultural uses, which would be far to supply the electricity consumption of the state (Farthing et al., 2016).

2.1.5. Conservation policy

Conservation policies allow to protected land for biodiversity and ecosystem functions. For this reason, conservation policy should aim at protecting a significant share of land to safeguard the resilience and stability generated by biodiversity (sometimes refered to as a “biodiversity buffer”). For example, the Brundtland Report and the calculation of the standard ecological footprint consider a 12% of the territory (Wackernagel et al., 2002; WCED, 1987). This value can be considered a conservative lower bound, which has been strongly criticized as being unable to a

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ensure an effective protection of biodiversity (Vačkář, 2012). For example, the UNEP and IUCN give 17% as a reference value (Juffe-Bignoli et al., 2014), while Soulé and Sanjayan (1998) argued for a minimum share of 25-50%.

Close to 15% of the Earth's land and 10% of its territorial waters are currently covered by national parks and other protected areas. However, crucial biodiversity areas are being left out (8 in 10 key biodiversity areas worldwide still lack complete protection), key species and habitats are underrepresented and inadequate management is limiting the effectiveness of protected areas. In fact, less than 20% of countries have met their commitments to assess the management of their protected areas, raising questions about the quality and effectiveness of existing conservation. Countries in Latin America and the Caribbean protect the largest portion of their land, amounting to nearly 5 million square kilometers. About half of that is in Brazil, which boasts the world's largest protected land area system of 2.47 million square kilometers. Middle East has the lowest land protection rate of around 3%, equal to around 119,000 square kilometers measures (UNEP-WCMC and IUCN, 2016). In Europe, 21 % of the territory of European Environmental Agency member countries and collaborating countries consisting of protected areas (EEA, 2012).

Ever-increasing competition for land may endanger the integrity of currently protected areas. Most model studies either assume projected areas to be constant, or even ignore this category as a special land category. There is one major exception, which is the Sustainability First scenario as part of UNEP’s (2007) GEO4. Based on a minimum share of protected land by biome category, this study assumes that projected area would need to increase from 2009 to 2030 by up to approximately 400 MHa worldwide. Many of these areas may not enter into strong competition with other land uses, while some are clearly at the forest frontier (Smith et al., 2010).

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2.2. Environmental impacts of land-use change

Land-use change alters the ecosystems services (e.g. water) and critically affects biodiversity. Deforestation is one of the most striking effects globally, with rates of 8.3MHa/yr in 1990-2000 and 5.2 MHa/yr in 2000-2010 (FAO Stats, 2013). In an analysis of factors causing deforestation in 41 tropical countries, DeFries et al., (2010) showed that deforestation can be explained by urbanization and the net export of agricultural products.

This section encompasses focus on the three main environmental impacts of land-use change in terms of land-use change GHG emissions, deforestation and biodiversity loss. Although these impacts have been separated in subsections for the sake of clarity, there are many interrelations between them given their integration into biosphere processes.

Other relevant impacts not reviewed here are land degradation, which has a rate over 10MHa/yr (Foley et al., 2005; Pimentel, 2006), and the impact on water. Freshwater use is one of the planetary boundaries (Steffen et al., 2015). Hydropower production was 3,900 TWh in 2014 (REN21, 2015), with 0,5-7 W/m^2 of land density and using $3W/m^2$ as a plausible average, then around 15MHa of land are being permanently inundated by this source.

2.2.1. Land-use GHG emissions

Land-use emissions (agriculture, forestry and other land-use, i.e. AFOLU) are the second cause globally after the energy supply sector, with an estimated contribution of just under a quarter (~10–12 GtCO2eq/yr) of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management. Anthropogenic forest degradation and biomass burning (forest fires and agricultural burning) also represent relevant contributions. Annual GHG emissions from agricultural production in 2000–2010 were estimated at 5.0–5.8 GtCO2eq/yr while annual GHG flux from land use and land-use change activities accounted for approximately 4.3–5.5 GtCO2eq/yr (see Figure 6) (IPCC, 2014). Other IAMs that consider this source of emissions and could be used as reference are GCAM (Kyle et al., 2011; Wise and Calvin, 2011) and IMAGE (Stehfest et al., 2014).

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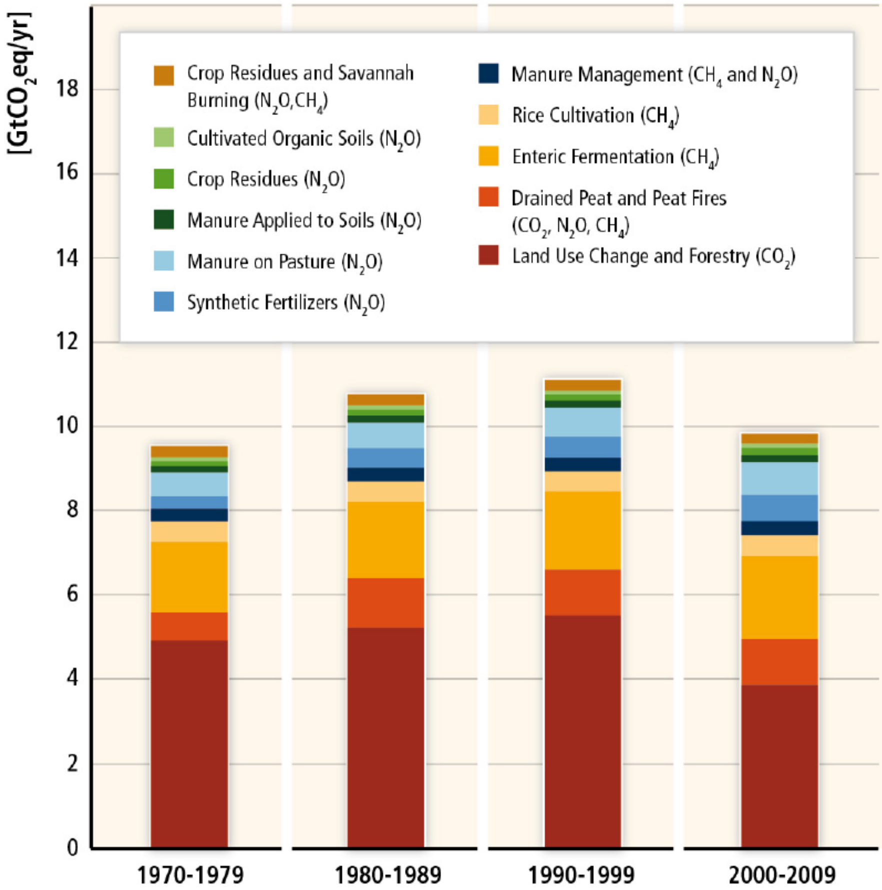

Figure 6 (IPCC, 2014): AFOLU emissions for the last four decades. For the agricultural sub-sectors emissions are shown for separate categories, based on FAOSTAT.

An example of indirect land-use change (ILUC) emissions is the situation caused by the EU policy to promote biofuels. The ILUC impacts of biofuels refer to land-use changes around the world induced by the expansion of croplands for ethanol or biodiesel production in the EU territory. Thus, a higher demand for biofuels could contribute to further conversion of forests, pastures and wetlands into agricultural land, crowd-out native vegetation and species, conflict with land and labor rights and lead to an indirect increase in GHG emissions.

As shown in Figure 7, when accounting for ILUC factors all biodiesel production in the EU is worse than fossil fuels in terms of GHG emissions (Laborde, 2011; Valin et al., 2015). Since biodiesel consumption accounts for around 80% in the EU, the implications of including ILUC factors are far from negligible.

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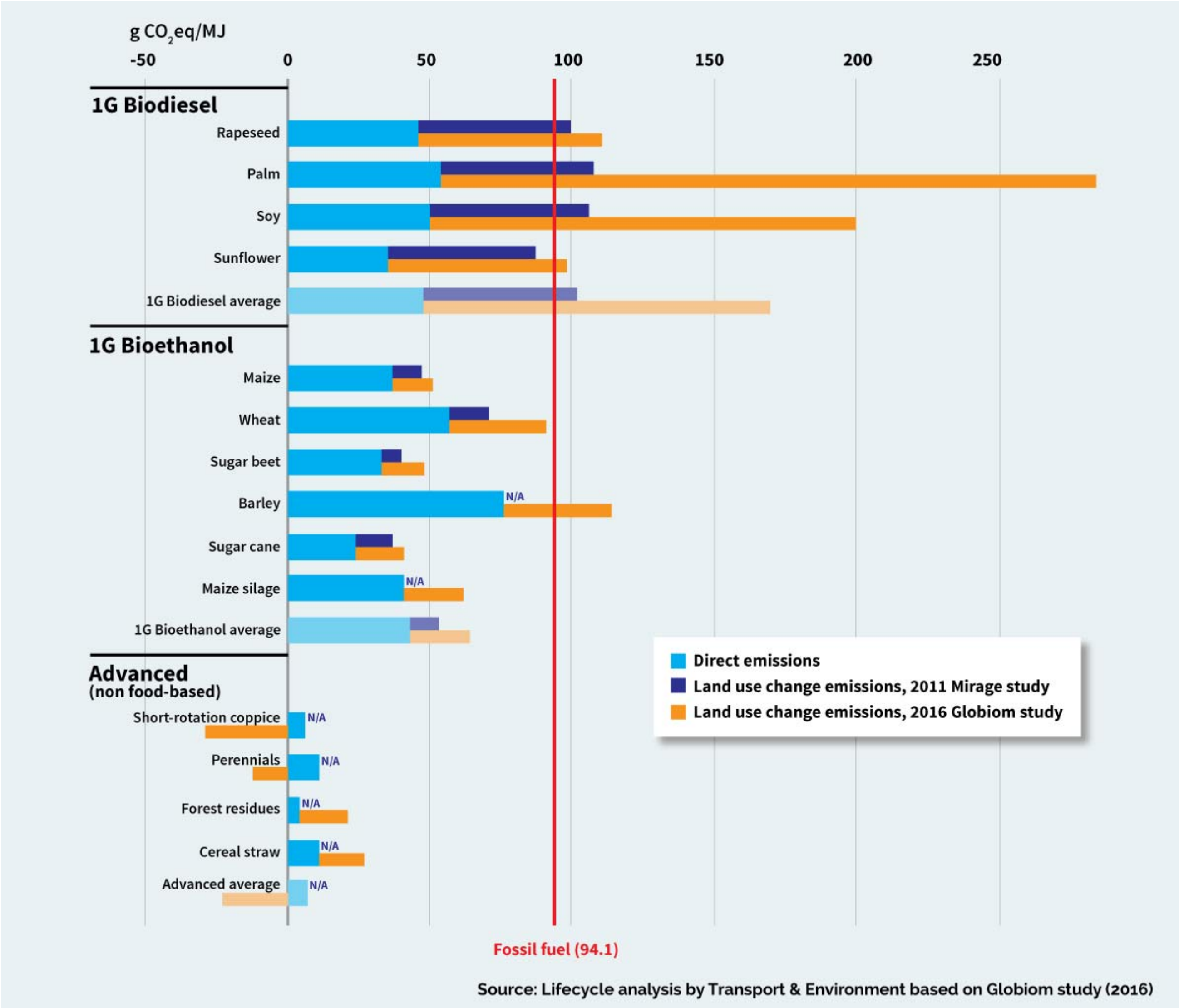

Figure 7: Biofuel emissions vs. fossil fuels emissions from two studies: Globiom (Valin et al., 2015) and Mirage (Laborde, 2011). Source: https://www.transportenvironment.org.

The Energy return on energy invested (EROI) of biofuels is much lower than fossil fuels. Assuming that EROI is less than 2 (de Castro et al., 2014), an average 100% increase of gCO_2e/MJ is obtained if accounting for net energy instead of gross energy. DeCicco et al. (2016) recently showed that "carbon uptake on cropland was enough to offset only 37% of the biofuel-related biogenic CO_2 emissions… [far] from the 100% assumption made by LCA and other GHG accounting methods that assume biofuel carbon neutrality", putting even more signals about their stronger impact on Climate Change than fossil fuel sources.

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Given that the future availability of technological ways to sequestrate carbon (such as carbon capture and storage CCS) is subject to many uncertainties and may even not be available at the large scale required (Fuss et al., 2014; Scott et al., 2013), afforestation and soil-management emerge as key strategies to store carbon (Hansen et al., 2016; Houghton et al., 2015; IPCC, 2014).

In fact, recent studies have found that climate policies focusing solely on industrial emissions may result in inconsistent mitigation policies due to terrestrial carbon leakages to non-participating regions (González-Eguino et al., 2016).

2.2.2. Deforestation

Forests occupy currently 4,033 MHa (2010 data), of which primary forest represents around 36% and planted forest occupation around 7%. Deforestation has decreased from an estimated 16 MHa/yr in the 1990s to about 13 MHa/yr in 2000s. The net change in forest area over the period 2000-2009 was estimated at -5,2 MHa/yr, down by 35% in the prior decade (FAO Stats, 2013).

2.2.3. Biodiversity loss

As seen in section 2.2.1, many countries are far from having protected a share of their territory to ensure the biodiversity protection: 8 in 10 key biodiversity areas worldwide still lack complete protection, key species and habitats are underrepresented and inadequate management is limiting the effectiveness of protected areas. In fact, less than 20% of countries have met their commitments to assess the management of their protected areas, raising questions about the quality and effectiveness of existing conservation (UNEP-WCMC and IUCN, 2016). As a consequence, the extinction rates have reached peak levels and biologists now suggest that a sixth mass extinction may be under way (Barnosky et al., 2011).

This biodiversity loss is extremely problematic given that it is a core planetary boundary. In fact, recent findings suggest the existence of a two-level hierarchy in biosphere processes, and climate change and biosphere integrity have been identified as core planetary boundaries through which the other boundaries operate. Both function at the level of the whole Earth System and have co-evolved for nearly 4 billion years. They are regulated by the other boundaries, simultaneously providing the planetary-level overarching systems within which the other boundary processes operate. In fact, transitions between time periods in Earth history have often been delineated by significant shifts in climate, the biosphere, or both. Each of these “core boundaries” has the potential on its own to drive the Earth System into a new state should it be substantially and persistently exceeded (Steffen et al., 2015).

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However, scientific debate is ongoing. For example, the MEA stated that "land use changes are perhaps the most critical aspect of anthropogenic global change in influencing the future of ecosystems and their services", while recognising that other global changes such as climate change and biodiversity loss may produce indirect effects on future ecosystem services with superimposed effects on land use changes (MEA, 2005). See for example Jones et al., (2013a, 2013b) for an analysis of the interactions between global climate change and land-use shifts.

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3. Results

Following the proposal of conceptual overview of the MEDEAS model (see Figure 8), the Land module would be directly linked with three other modules: Economy and Population (e.g. through food and services demand), Energy (e.g. through energy policies, i.e. land requirements of different energy mixes) and Climate (e.g. through land-use change CO_2 emissions) (GEEDS, 2016).

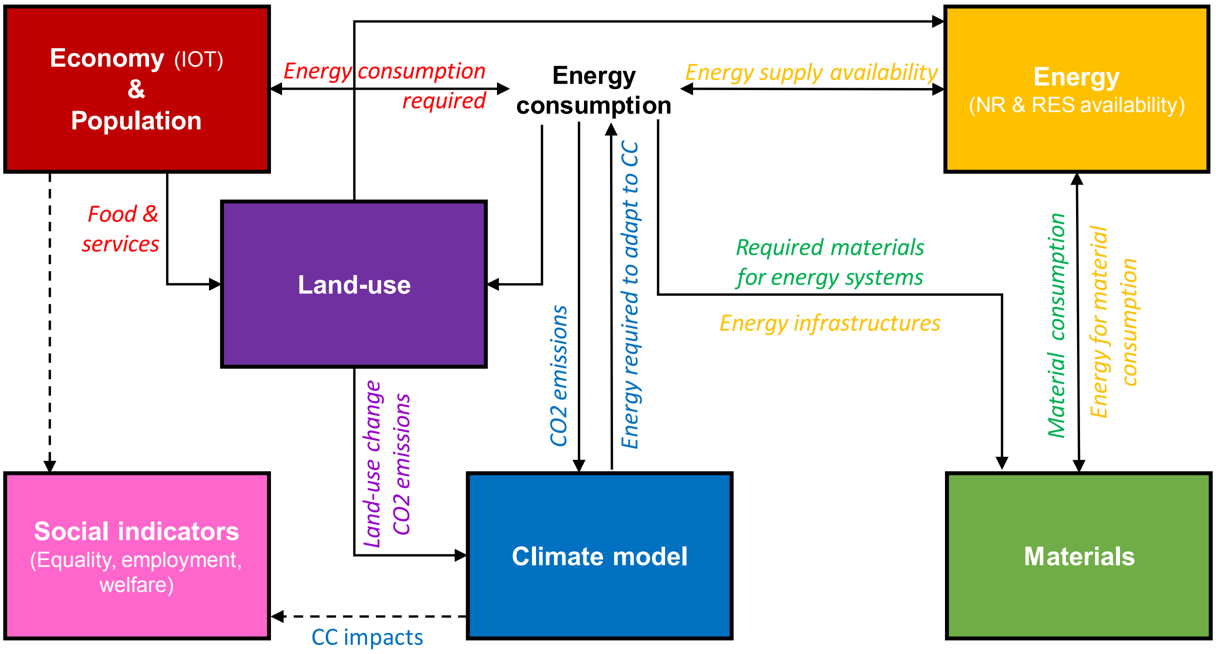

Figure 8 (GEEDS, 2016): Schematic module interactions of MEDEAS framework.

In this framework, the Land module represents the different human uses of land as well as the natural land. If population keeps growing following the current patterns, there will be increasing needs of land for agriculture and urbanization, which in combination with the trends of land degradation will increase the competition for land. Similarly, some RES resources that do not allow for double uses (such as biocrops and solar power plants) require large areas of land due to their low power density, a land limit extensible to wind energy. Finally, the growth in forests cover due, for instance, to afforestation programs to store carbon and improve biodiversity, also increases the land-use requirements. Hence, the land-use module will confront the demand of land to cover different needs with the biophysical land availability (see Figure 9).

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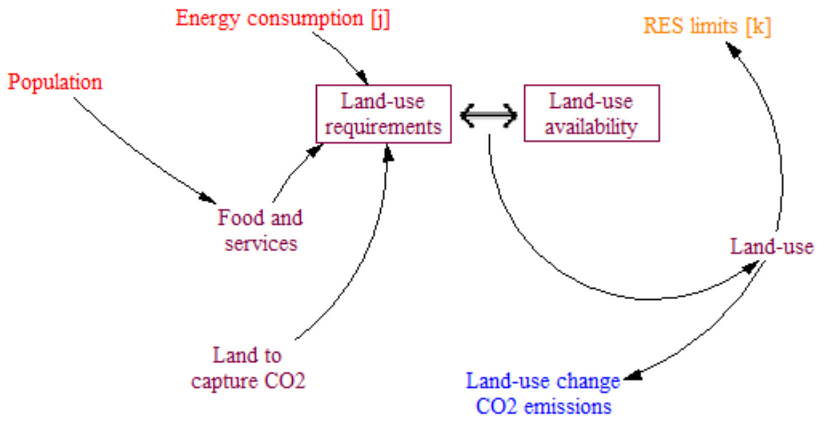

Figure 9 (GEEDS, 2016): Extended land use module.

Summarizing, the Land module will be directed to cover two main objectives:

1. Assess the potential restrictions that land availability might impose to RES deployment,
2. Estimate the land-use change GHG emissions to feed the climate model.

First of all, robust projections of future food requirements (including diets), urbanization and infrastructures expansion, degraded land, required land for preserving biodiversity should be built at both global and European level. These projections will be challenged by the fact that they are dynamically affected by other modules of MEDEAS. For example, degraded land and biodiversity conservation trends will be critically affected in the future by the level of global environmental change. Subsequently, the literature review indicates that for the first objective the efforts should be focused into estimating the demand and supply of solar and bioenergy (including all uses such as biopower, biofuels and bioheat) and the land requirements of water reservoirs for pumped hydro considering their surface power densities. This could be eventually extended to other sources such as wind. The rest of energy infrastructures (other energy technologies) as well as additional infrastructures for transportation might be not considered as a first approximation or included as a share of the growth in urbanization/settlements.

For the second objective, the storage capacity of carbon by different types of land use should be assessed, taking into account that the processes of carbon loss and accumulation are inherently dynamic. Other IAMs that consider this source of emissions and could be used as reference are GCAM and IMAGE.

Human infrastructures already occupy today between 1 and 2% of total terrestrial land globally. This number increases to 5% in some densely populated countries, located mainly in temperate

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climatic zones. In high mountains, hot and cold deserts and tropical forested zones, human density population are much lower and therefore human infrastructure densities follow. It will be very difficult, as well as very intensive from a social, economic, material and energetic point of view (and very likely unsustainable), to increase the human infrastructures to 1-2% in deserts, high mountains, continental sea platforms or any other territories with low human footprint. Human infrastructures are netted systems embodied in natural ecosystems. "Island" type infrastructures are very scarce (like an oil offshore platform) and only are far away of other infrastructures when they are a "hot spot" of a very interesting material for a concrete civilization or culture (a gold mine, a high energy density natural gas field etc.). But, if the material is very dispersed or far, then the "civilization" must follow (e.g. a cultivated land, a water reservoir, fracking oil fields, solar resources, etc.).

MEDEAS will generate demand trends of different energy technologies that will be dynamically matched with the supply availability factors (i.e. materials, infrastructure deployment rhythms (i.e. time), etc.) being land availability one of them. For the land module, stocks and growth trends should be built (following the scenario methodology) for urban/settlements, agricultural land, forest land, degraded land and hot deserts. As the literature review shows, usually the urban/settlements growth at the expense of agricultural, the agricultural at the expense of forest, the degraded land at the expense of forest and agricultural, and deserts due to global environmental change and at the expense of degraded lands. Two more stocks could be added to model bioenergy (at the expense of forest and agricultural land, and in the case of a sustainable scenario at the expense of degraded land), and land for solar (at the expense of agricultural land, degraded land and –depending on the scenario- desert land). As the model runs different impacts in terms of climate change, biodiversity loss will be assessed depending on the scenario. In particular, climate change might also feedback the Land module causing loss of agricultural and forest land and increasing the degraded land and deserts.

Summarizing, for the implementation in MEDEAS, a review of the historical data of land use categories (from FAOSTATS and EUROSTAT) as well as of the historic drivers of land-use change at both global and European level have been done. Given that substantial levels of both food and energy (mainly in the form of biomass) can be imported, assumptions about energy and food security should be made for the regional modeling of Europe within the global model. Other variables as water may be important for the robustness of the land-module given the dependency of crops (and some energy technologies) of the availability of this resource.

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4. Conclusions

The present review indicates that land is a critical component of any analysis focusing on sustainability and that its consideration qualitatively modifies the results obtained by energy-economy-environment models. This review also shows that the main drivers of land-use will continue to operate in the next decades: population growth, urbanization trends and shift to more land-intensive diets (Kastner et al., 2012; Smith et al., 2010). Weinzettel et al., (2013) found a 70% increase in the global land footprint by 2050 compared to 2004 under business-as-usual conditions, the area of unexploited bioproductive land being reduced from 34% to 6% of global biocapacity. Moreover, additional factors may arise in the next decades as a result of the promotion of renewable energies and climate policies.

The dedication of land to produce energy has been identified as a potential concern not only for preserving natural ecosystems, their services and biodiversity, but also because of its competition with land use to cover human needs (i.e., food, fiber, shelter and infrastructure). These concerns rise in parallel with the current rapid expansion of modern renewable energy technologies and the steady decrease in their costs over recent years (Deutsche Bank, 2015; REN21, 2015). Thus, this transition could aggravate existing vulnerabilities and create new ones in terms of energy security, biodiversity loss, and food sovereignty, among others (Capellán-Pérez et al., 2016; Johansson, 2013; MacKay, 2013; Nonhebel, 2003; Rao and Sastri, 1987; Scheidel and Sorman, 2012). Given that the future availability of technological ways to sequestrate carbon (such as carbon capture and storage CCS) is subject to many uncertainties and may even not be available at the large scale required (Fuss et al., 2014; Scott et al., 2013), afforestation and soil-management emerge as key strategies to store carbon (Hansen et al., 2016). The EU is especially vulnerable to future developments given its current high dependence on foreign land. The EU uses for its consumption about 1.5 times its own territorial land use abroad, mainly in Latin America and Africa.

Table 1 summarizes the main drivers and variables to be considered in the Land Module of MEDEAS assessed in this report.

Table 1: Analysis of drivers and variables to be considered in the Land Module of MEDEAS.

Drivers of land-use change	**Variables to be considered in MEDEAS (* indicates priority variables)**

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Expansion of urbanized areas	Population evolution*, urbanization tipology
Increasing food and fiber demand	Diets*, land-use practices and management, water availability
Energy policy	Energy demand*, Energy mix*, RES deployment*, surface power density per technology*
Climate policy	Sequestration of carbon in ecosystems*
Conservation policy	Land-use protection*
Environmental/climate change impacts	Soil loss*, erosion, crop yields

MEDEAS will generate demand trends of different energy technologies that will be dynamically matched with the supply availability (i.e. materials, infrastructure deployment rhythms (i.e. time), etc.) being land availability one of them. The Land module in MEDEAS will be directly linked with -at least- three other modules: Economy and Population (e.g. through food and services demand), Energy (e.g. through energy policies, i.e. land requirements of different energy mixes) and Climate (e.g. through land-use change CO_2 emissions). This module will cover two main objectives: (1) assess the potential restrictions that land availability might impose to RES deployment (mainly bioenergy, solar and pumped hydro), and (2) estimate the land-use change GHG emissions to feed the climate model.

First of all, the relationship between the drivers and the impacts of the variables of the Economy and Land submodules at both global and European level should be modelled. Subsequently, projections of future food requirements (including diets), urbanization and infrastructures expansion, degraded land, required land for preserving biodiversity should be built in a scenario methodology framework. These projections will be challenged by the fact that they are affected by other modules of MEDEAS. For example, degraded land and biodiversity conservation trends will be critically affected in the future by the level of global environmental change. Given that substantial levels of both food and energy (mainly in the form of biomass) can be imported, assumptions about energy and food security should be made for the regional modeling of Europe

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within the global model. Other variables as water may be important for the robustness of the land-module given the dependency of crops (and some energy technologies) of the availability of this resource.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

List of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Appendix

A.1 Land footprint in the European Union

The land footprint refers to the total land required to satisfy the consumption of goods and services in an economy (including the net embodied land in international trade). In 2008, the share of the land footprint covered with domestic land use (i.e. the land footprint coverage ratio) was 45% in the EU-27.

Between 1995 and 2008, the share of the land footprint of the EU-27 covered by domestic land fell from 47% to 45%. In this period, most Member States reduced their domestic coverage ratios. In 2008, only Estonia (121%), Bulgaria (120%) and Finland (103%) showed a domestic coverage ratio above 100%. Malta (2%), the Netherlands (7%) and Belgium (9%) were the countries with the lowest figures, followed by Cyprus (21%) Luxembourg (22%), Germany (23%) and the United Kingdom (24%) (see Figure 10).

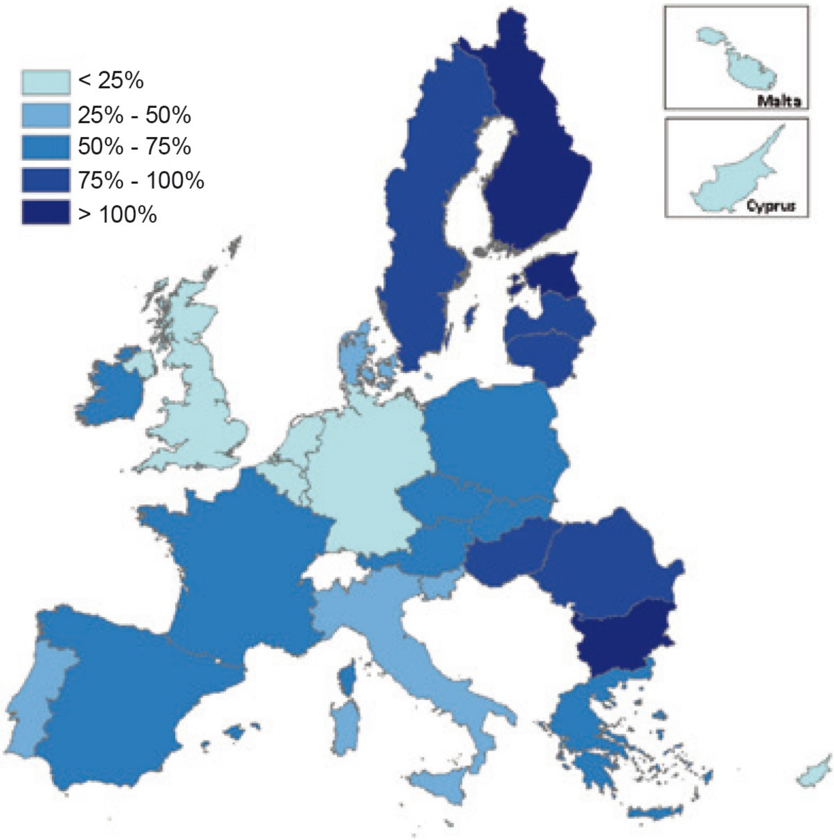

Figure 10 (Arto et al., 2012): Land footprint domestic coverage ratio, EU-27, 2008 (%).

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In the EU-27 (2008), food, drinks, and tobacco (64%), recreation and culture (10%), restaurants and hotels (8 %), and clothing and footwear (4%) were the consumption activities that caused most of the land footprint (see Figure 11).

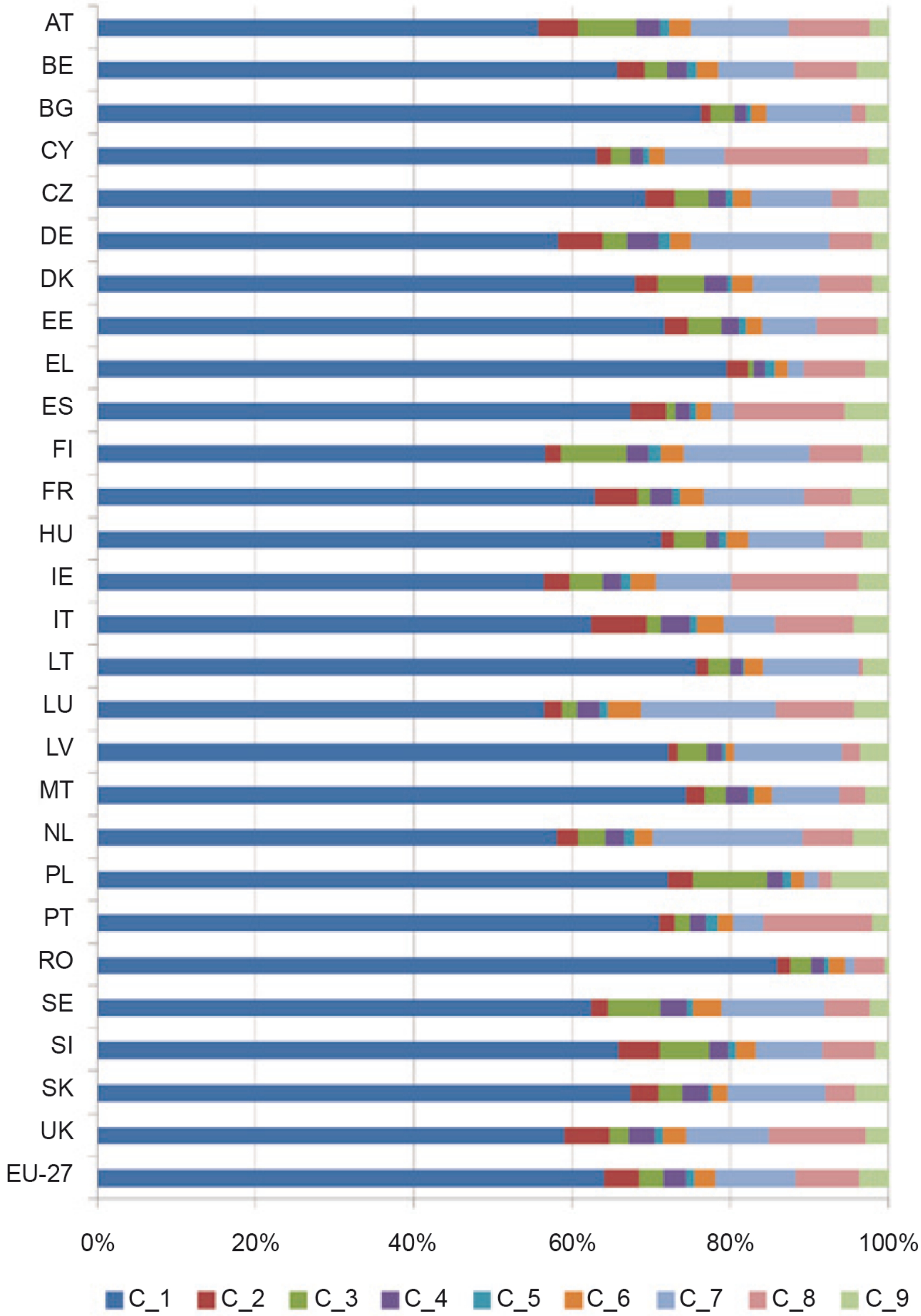

Figure 11 (Arto et al., 2012): Household land footprint by consumption category, EU-27, 2008 (%). NB: C_1: Food, drinks and tobacco; C_2: Clothing and footwear; C_3: Housing, fuel, and power; C_4: Household goods and services; C_5: Health and education; C_6: Transport and Communications; C_7: Recreation and culture; C_8: Restaurants and hotels; C_9: Miscellaneous goods and services.

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