Title

Chapter 2

Permalink

https://escholarship.org/uc/item/4xf126hm

Authors

Loqué, Dominique
Eudes, Aymerick
Yang, Fan

Publication Date

2011-09-09

DOI

10.1039/9781849732857-00005

CHAPTER 2

Biomass Availability and Sustainability for Biofuels

DOMINIQUE LOQUÉ, AYMERICK EUDES
AND FAN YANG

Feedstocks Division, Joint BioEnergy Institute, Physical Biosciences
Division, Lawrence Berkeley National Laboratory, Berkeley, CA

2.1 Introduction

On earth, only 29.2% of the surface is land (149 million km^2) and the rest is covered ocean. From this 29.2%, only 59.5% is considered as biologically productive land (88.6 million km^2) which corresponds to forests (39.3 million km^2) or agricultural areas (49.3 million km^2). Biologically productive land corresponds to land that supports human demands for food, fiber, and timber for infrastructure and energy (FAO definition). The other 40.5% of lands, considered as non-productive lands, have a very low or no primary productivity since they are covered by ice, water, or constructions, or they are located under extreme climate conditions (cold, dry, or arid). The productive lands are divided into several biomes, primarily classified according to the vegetation types and productivity,[1] which are dictated by the climate and human accessibility. In order to define which lands can be transformed as bioenergy lands (biofuel lands), an evaluation of most of the primary lands has to be conducted and will be presented in this section.

RSC Energy and Environment Series No. 4
Chemical and Biochemical Catalysis for Next Generation Biofuels
Edited by Blake Simmons

Published by the Royal Society of Chemistry, www.rsc.org

2.2 General Land Types

2.2.1 Forest Lands

Forests cover approximately 39.3 million km^2 and are divided into three main types: boreal, tropical, and temperate (Table 2.1). Boreal forests represent 13 million km^2, 33% of the total forest, and correspond to forest growing in cold areas (yearly average temperature +5 to –5 °C) and a short growing season with an aboveground biomass accumulation of 2.3 t/ha/year.[2] They are mainly found in the northern part of the northern hemisphere and in some mountains at high altitudes. Coniferous trees are the dominant species, also called 'evergreen'.

The temperate forests cover 9.8 million km^2, 25% of total forest,[2] and are found in a more moderate climate and in both hemispheres. The diversity of tree species is much larger than the boreal forest and varies significantly between both hemispheres. The dominant species eucalyptus, Nothofagus, Araucaria, and Podocarpus are predominant in the southern hemisphere and pine, sequoia, oak, maple, and birch are preferentially in the northern hemisphere. The temperate forests cover a smaller surface than the boreal or tropical forests. They are mainly found on low quality soils (sandy, rocky, etc.), on poorly accessible areas or in isolated areas, which correspond to lands that are usually classified as non-suitable for farming. This is explained by a large deforestation during the past centuries that were made to increase agricultural area and was responsible of the conversion of the best forestlands into croplands. The approximate aboveground biomass accumulation of temperate forests is estimated at 9.5 t/ha/year.[2]

Table 2.1 Summary of submerged-lands.

		Area			*Productivity*
		(M km^2)	*%*	*%*	*(t DM/ha/y)*
Forest lands	boreal	13	33		2.3
	tropical	9.8	25		9.5
	temperate	16.5	42		14
		39.3		**26.4**	
Agricultural lands	very suitable	13.5	27		18–22
	suitable	15.1	31		13–17
	moderately suitable	7.9	16		10–12
	marginally suitable	5.4	11		4–7
	non-suitable	7.4	15		<2
		49.3		**33.1**	
"Non-biologically" productive lands	Desert	31.5	52		1.5
	Tundra	5.6	9		0.8
	Rest (urban area, rivers, glacier...)	23.3	39		
		60.4		**40.5**	
Submerged lands		**149**			

(Data extracted from: http://faostat.fao.org with 2008 as reference year, Terrestrial Global Productivity[2], and several other resources.[5,6,10])

Tropical forests represent almost 50% of the world's forest and cover 16.5 million km^2, 11% of the available land.[2] They are mainly found under the wet tropical climate located around the equatorial regions with a monthly temperature average above 18 °C and a monthly rain above 100 mm monthly.[3] These giant forests contain the largest species diversity that has been estimated at over $>65\,000$.[4] Tropical forest is the biome that has the highest biomass productivity, with a total aboveground biomass accumulation of 14 t/ha/year approximately.[2]

2.2.2 Agricultural Lands

Forests cover 45.7% of biologically active lands at 49.3 million km^2, and correspond to lands that have an agricultural potential and are mainly represented by croplands and pastures (Table 2.1). It is estimated that 31% of these lands (15.5 million km^2) are used for food and feed production. From the 38.8 million km^2 designated as pastures, it is estimated that 70% (26.4 million km^2) has the potential to be converted to croplands since they would be suitable for rain-fed agriculture.[5]

From the 49.3 million km^2 of agricultural lands, 41.9 million km^2 of lands are considered to be suitable lands for crop production and are divided as 13.5 million km^2 as very suitable crop lands with a productivity of 18–22 t DM/ha/year, 15.1 million km^2 as suitable crop lands with a productivity of 13–17 t DM/ha/year, 7.9 million km^2 as moderately suitable crop lands with a productivity of 10–12 t DM/ha/year, and 5.4 million km^2 as marginally suitable crop lands with a productivity of 4–7 t DM/ha/year.[6] These lands were classified according to their potential food-crop productivity for rice, wheat, corn, or soybean. Interestingly, most of these potentially available lands would come from developing countries and the very suitable, suitable, moderately suitable, and marginally suitable land correspond to 80–100%, 60–80%, 40–60% and 20–40% respectively of the maximal attainable annual biomass.[5] The estimation of productivity is based on *Miscanthus* yields produced in Eastern Europe.[6] The conversion of pastures into croplands needs to be conducted with caution to avoid irreversible losses since it is already estimated to 3.1 million km^2 of lands have been severely or irreversibly degraded since 1945 due to severe chemical degradation and/or erosion.[7,8] It is also estimated that 38% (5.9 million km^2) of actual croplands are suffering from degradation and consequently have lost part of their respective productivity potential.[8] It is also important to note that from the 15.5 million km^2 of rain-fed croplands, 2.9 million km^2 are assisted by irrigation, which, over the long term, is partially responsible for land degradation.[9]

2.2.3 Desert Lands

A third large area, which represents 21.1% (31.5 million km^2)[10] of available lands, corresponds to the desert ecosystems that are not part of the biologically productive lands so far (Table 2.1). Deserts are usually found in areas that have the lowest and most irregular yearly rainfalls (below 250mm/y), and, consequently, have very low biomass productivity, typically below 1.5 t/ha/year.[2] Arid, semi-arid, and coastal deserts are constantly expanding due to desertification, a physical process which is very frequently caused by human activity. Desertification in arid areas is not a phenomena that is only associated to a lack of precipitation, it can be indirectly caused by reduction of the vegetative cover due to nutrient deficiency, mainly nitrogen and phosphorus deficiencies, overgrazing, erosion, and salt stresses.[11–13] In fact, the decline of the vegetative cover reduces the organic matter that can retain moisture in the soil and nutrients, but also increases soil evaporation and soil erosion. The main plant species found in the desert are short life cycle annual plants and drought stress-tolerant plants such as shrubs, succulents, and few trees.

2.2.4 Tundra Lands

The last major biome on earth, tundra, is the coldest ecosystem, and together with the desert biomes have the lowest biomass productivity on earth. The small amount of rainfall and limited number of days with a temperature that goes above 0 °C renders the area not suited for trees. The plant species able to grow under these extreme conditions are mainly small numbers of specialized mosses, grasses, lichens, and shrubs.[14] Growth primarily occurs during the continuous daylight that occurs in summer after the snow is melted and the ground defrosted. This biome is mainly found near the polar circle on the border of the boreal forests. This biome covers about 5.6 million km^2.[2] Even if the biomass productivity (0.8 t/ha/y)[2] is as low as or even lower than the desert ecosystems, the carbon stored in the underground is very important due to the low biomass degradation rate.[15,16]

2.3 Potential Bioenergy Feedstock Lands

Lands that could be potentially suitable for biomass production for biofuels need to be lands that have enough productivity to render this approach financially sustainable. The higher the land productivity will be, the lower the quantity of land surface required to meet the needs and lower the ecologically impact will be. However, the most productive lands are either the tropical forests that should be protected or the best croplands already used for human agriculture. Lands that are still productive but non-sustainable for food production, are called marginal lands. They would potentially represent 28 million km^2. Switchgrass, one of the potential bioenergy crops, has a yield varying between 5.6 and 18 t DM/ha/y, depending on the species and geography, but a majority of them yield above 10 t DM/ha/y.[17] The growth of bioenergy crops, such as switchgrass, on 28 million km^2 yielding at 10 t DM/ha/y (low-end yield), would generate 28 billion t/y of dry biomass, which represents approximately 518×10^{18} J/y (2.8 billion ha × 10 t/ha × 18.5 billion J/t DM).

The amount of energy that could be potentially produced on the lower quality of biologically active lands is just above the actual worldwide energy consumption estimated at 498×10^{18} J in 2006 (http://www.eia.doe.gov/oiaf/ieo/world.html) or 393×10^{18} J (80.1% of total energy: gas, oil, and coal) from fossil fuels.[18] The amount of arable lands left over corresponds to the topsoil lands and represents double of what is currently used for food production. The production of energy from biomass could be further extended since the proposed land does not include any forest lands, in fact doubling the surface of the currently managed forest lands, estimated at 3% (1.18 million km^2) and corresponding of boreal and temperate would have the potential to generate more biomass without competing with food crop lands.

The proposed bioenergy croplands could be reduced if the selection of the bioenergy crops is done according to the available land quality and if breeding programs are developed on dedicated bioenergy crop species. For example, in the paper industry significant improvements have been achieved to improve pulping efficiency and yield, and are mainly attributed to an increase of timber yield and quality which have been addressed by genetic improvement and better forest management, and finally by better conversion processes.[19–23] This suggests that similar improvements of energy crops and conversion techniques have the potential to reduce the land area required to replace the 393×10^{18} J produced from fossil fuels[18] and/or to compensate for the constant augmentation of worldwide energy consumption. In addition, the lands proposed as bioenergy crop lands could be reduced if abandoned lands and non-biologically-active lands (FAO definition) are targeted for bioenergy production. Additionally, there is a huge amount of unused biomass generated on various lands; forest lands, agricultural lands, and city lands, available for conversion.

2.4 Bioenergy Feedstocks

Plants are divided into three main groups according to their longevity; annual, biannual, and perennial. These groups have common and complementary agronomical properties that are fully used by farmers and landscape managers. With the vision of land sustainability and low input, (energy, time, and fertilizer), in general, perennial plants have a serious advantage. They have the ability to grow on marginal lands and to avoid land degradation especially caused by erosion (water, wind, and water) since they can fix the soil and bring a yearly land coverage in contrast to annual plants that have a dead time of land coverage between the end of the fruiting time and the newly developed plant. The planting of perennial species on degraded lands or abandoned farmlands can be converted into biofuels sustainably as they represent feedstocks produced with little or no competition with food production since these lands are usually improper or unsustainable for food crop production. The use of perennial plants that require little input in terms of fertilizer and can be grown on rain fed water, have the benefits of generating a lower greenhouse gas emissions than traditional fossil fuels. However, double crops and mixed cropping systems are also considered for biofuel production since some of them have the potential to keep a permanent vegetative cover to mitigate the potential risk of land degradation due to erosion.

Similarly to any other crop, high biomass yields obtained from dedicated bioenergy crops is desirable. This can be achieved through the improvement of several traits to maximize photosynthesis. These include improving light radiation interception, use efficiency, and CO_2 fixation efficiency.[24,25] In particular, leaves could be more efficient at capturing light and CO_2 to show higher photosynthesis rates. Plants able to grow under high density and developing canopies with low extinction coefficients are considered to intercept more light radiation. Additionally, the prolongation of the light capture time and CO_2 fixation could be achieved by the extension of the vegetative growth using plants with a delay of senescence.[26–29]

Bioenergy crops should also meet the traits usually favored in traditional agriculture such as cold and drought tolerance, resistance to lodging, efficient and flexible in terms of water use, disease and pest resistance, and high nitrogen-use efficiency. Nitrogen is a very expensive nutrient when it needs to be manually supplied since nitrogen fertilizers require a lot of energy to be made and intensive supply create lot of environmental disasters. Also, plants providing insufficient biomass for harvest during their first year of culture should show winter standing capacity, as it would improve the light capture efficiency during the following years.

Furthermore, in order to ensure environmental and financial sustainability of dedicated bioenergy crops, several plant traits that would minimize fossil fuel inputs and nutrient depletion have to be considered. They include efficient nutrient recycling to the roots and remobilization, optimal root/shoot partitioning, low nitrogen requirements, and efficient use of water. Bioenergy-crops adapted to wastewater supply, polluted, and salty conditions represent attractive resources, as they would not compete with the water dedicated for food crops. Bioenergy crops able to grow on poor soils or marginal lands would not occupy lands required for food crops and offer the opportunity of restoring eroded lands by sequestering additional soil carbon. Bioenergy crops should be non-invasive or sterile in order to control their spatial distribution to avoid ecological catastrophes.

Alternatively, multiple-use scenarios for which crops that produce food and crop residues for biofuel can be considered. However, the amount of crop residue that can be removed from the soil has to be determined carefully in order to not impact soil and environmental quality as well as future crop yields grown on those lands.[30]

Sustainability of bioenergy crops will increase if they are adapted to farming systems (i.e. equipment, transport) and suitable crop rotation patterns, harvesting, and storage. Consequently, plants should be easily removed from the soil and grown from seeds, should generate straight with upright stems, have low moisture content and high sugar density, and finally should be resistant to microbial breakdown during post-harvest. Plants that provide enough biomass during the first year of planting would be desirable to optimize the harvest and productivity.

After harvesting, multiple conversion methods and flexible processing of the biomass should be employed to maximize the value of the feedstock. Plants such as sugarcane represent feedstocks requiring low or no pretreatment to harvest soluble sugars as opposed to lignocellulosic biomass, which requires pretreatment and hydrolysis processes prior to fermentation of the released sugars.

Several plant species are already considered as good candidates since they fulfill part of requirement described above to be a good bioenergy crop (Table 2.2). These crops can be categorized as 'energy cane' such as sugarcane, perennial warm-season grasses (WSGs) such as *Miscanthus*, switchgrass, and sorghum, and short-rotation woody crops (SRWCs) such as poplar, willows, and eucalyptus. WSGs have high biomass yield, deep-root system, rapid growth, low-maintenance, greater adaptability, and higher drought tolerance as compared with other common grass species.[31] Growing perennial WSGs does not require intensive cultivation or soil disturbance after establishment, which potentially offers soil and environmental improvements. Because WSGs enhance nutrient cycling and storage, and deep rooting system, they may require lesser amounts of fertilizers and may suffer less of water limitation than annual food crops. The magnitude of benefits of growing WSGs will depend,

Table 2.2 Properties of different plant species considered for bioenergy-crops.

	Sugarcane	Miscanthus	*Sorghum*	*Switchgrass*	*Short-rotation trees (Poplar, Eucalyptus)*
Efficient photosynthesis	■	■	■	■	
Long canopy duration	■	■	■	■	■
Nutrients recycled to roots		■		■	■
Low crop inputs		■	■	■	■
Low fossil fuel inputs		■		■	■
Adapted to marginal land		■	■	■	■
Minimal pests/plant diseases		■		■	■
Non-invasive or sterile	■	■	■	■	■
Easily removed	■	■	■	■	■
Winter standing	■	■		■	■
High water-use efficiency	■	■	■	■	■
Planted by seed			■	■	■
Harvest first year			■		
Adaptation to farming systems	■	■	■	■	
Genetic/biotechnology		■		■	■
Low pretreatment cost to obtain sugars	■				

however, on the culture management; harvest frequency, cutting height, and energy density.[31]

SRWC can be harvested faster after establishment compared to traditional forestry,[32] and economical losses and recovery time from wildfire will also be reduced. Plantations of SRWCs generate high input of leaf and root litter, coupled with reduced soil disturbance, which benefit soil properties by minimizing crusting. Growing SRWCs such as *Salix* and *Populus* spp. influences soil aggregate stability, aggregate strength, soil porosity, soil water retention, and aeration. The SRWCs can also improve soil water retention over cultivated soils due to their greater soil organic matter concentration.[33] Greater accumulation of soil organic carbon under SRWCs will occur when trees are grown in marginal and eroded lands rather than in croplands or natural forests.[34] SRWC produces more biomass over longer periods of time (12–15 years) and a higher biomass/sugar density compared to WSGs, thus representing more manageable reserves of feedstock supplies that do not require frequent harvest and storage processes.

Growing dedicated plants with the bioenergy crop properties (see above and Table 2.2) would minimize the use of the land dedicated and potentially available for food crops and would have a lower impact on the natural diversity found on marginal lands. Additionally, the use of degraded or polluted lands not suitable for food crops to produce biofuel crops could be restored as good land and potentially become suitable for food production. Perennial energy crops (trees and grasses) have the ability to remobilize nutrients in their root system during senescence, offering a source of minerals and organic matter in the soil after harvesting the aboveground biomass. Alternatively, depletion of toxic compounds from the soil could be achieved when growing plants capable of extracting and accumulating high levels of pollutants such as heavy metals in their aboveground tissues. The ability of WSGs and SRWCs to grow on lands with deteriorated soil conditions that are not appropriate for growing conventional crops suggests that some agricultural lands can be used to produce biofuel feedstocks and become profitable.

Feedstocks subtracted from fertile lands (i.e. lands already occupied with food crops) could be the biomass produced from double crops and mixed cropping systems. For example, bioenergy crops grown and harvested before the sowing and growing seasons of conventional food is an example of land-use options with potential to produce biofuel feedstocks under good management without decreasing food production and without clearing wild lands.[35] It could have the advantage of creating a plant cover during intercropping which would have the advantage of reducing soil erosion. Mixed cropping systems in which food and energy crops are grown simultaneously is another possibility.[36] Finally, plants such as alfalfa are considered as a feedstock in a 'multiple-use' scenario – the fractionation of alfalfa into a leaf fraction for high quality forage and a stem fraction for cellulosic biofuel.[37]

Biotechnology and the design of genetically improved plants would considerably upgrade bioenergy crops sustainability. Such approach is aiming at improving biomass properties in terms of growth efficiency, quantity, and quality (i.e. biomass degradability and added value). Example of poplar genetic transformations were first published 20 years ago and various poplar species have been studied for genetic engineering purposes, with for example the deregulation of specific genes involved in biomass quality.[38] Switchgrass transformation protocols are also now well established and open an avenue for genetic improvement.[39] The potential genetic transformation of willows and *Miscanthus* is less advanced, but research on embryogenic suspension culture and the transformation of callus tissue of *Miscanthus* via microprojectile bombardment, suggest that the generation of transgenic *Miscanthus* clones should be possible in the near future. In particular, plant height is one of the most important biomass yield components for which key controlling genes and pathways have recently been identified. Manipulating plant height in model species using genetic engineering was recently achieved, and several genomic regions that influence plant height in maize and sorghum have been identified.[40]

2.5 Degraded and Non-productive Lands

The international Soil Reference and Information Center (ISRIC) and the United Nations Environment Programme (UNEP) published a report on the degradation of agricultural lands due to erosion in a document entitled 'World Map of the Status of Human-Induced Soil Degradation'.[41] Land degradation is a natural process, but it is very often accelerated by human activities such as over-grazing, over-cultivation, over-irrigation, deforestation, and industrial pollution. This degradation can also be caused by the accumulation of organic pollutants, heavy metals, or salt, water, wind, or drought stresses, and will commonly be associated with erosion processes. In the GLASOD report[41] the authors claim that a total of 19.64 million km^2 were degraded worldwide in 1991. Water erosion apparently affects 10.94 million km^2 (56% of the total area suffering degradation). Wind erosion affects 5.48 million km^2 (38% of the degraded terrain). Loss of topsoil through water erosion is the most common type of soil degradation. It occurs in almost every country, under a great variety of climatic and physical conditions and land use. As the topsoil is normally rich in nutrients, a relatively large amount of nutrients is lost together with the topsoil. This process may lead to an impoverishment of the soil. Loss of topsoil itself is often preceded by compaction and/or crusting, causing a decrease in water infiltration capacity of the soil, and leading to an accelerated run-off and soil erosion. Loss of topsoil can also result from wind action. It is a widespread phenomenon in arid and semi-arid climates, but it also occurs under more humid conditions.

In general, coarse-textured soils are more susceptible to wind erosion than fine-textured soils. Wind erosion is nearly always caused by a decrease of the vegetation cover of the soil, due to overgrazing, pollution, salt stress, or removal of vegetation for domestic or for agricultural uses. In semi-arid climates natural wind erosion is often difficult to distinguish from human-induced wind erosion, but natural wind erosion is often aggravated by human activities. Growing conventional crops that require high inputs on these lands could increase rates of erosion and polluted runoff. Erosion is often associated with a reduction of vegetative cover, which increases the eroding power of the wind and water, which if not stopped in time ends up with desertification. Loss of nutrients and/or organic matter occurs if agriculture is practiced on poor or moderately fertile soils without sufficient application of manure or fertilizer. It causes a general depletion of the soils and leads to the decreases of plant biomass and land productivity. Loss of nutrients is a widespread phenomenon in countries where low-input agriculture is practiced. The rapid loss of organic matter after clearing the natural vegetation is also included in this type of soil degradation. The loss of nutrients by erosion of fertile topsoil is considered to be a side effect of erosion, and not distinguished separately.

The use of bioenergy crops on these lands, which are improper or non-sustainable for food production generate multiple ecological and economical benefits. For instance, these bioenergy crops could be used to stop land degradation and to restore soil fertility, thus it would act positively on carbon sequestration and reduce water pollution generated by the soil erosion. It would create biomass designated for bioenergy production, which will have a positive impact on the reduction of fossil-fuel consumption and it should generate financial incomes. Finally, the use of these degraded lands would not compete with lands designated for food production.

2.5.1 Abandoned Lands

In general, food crops are very nutrient demanding and are very sensitive to various stresses, thus they require active management that is very costly. Consequently, lands that are poorly productive and not economically sustainable (financial input > financial output) get abandoned. Most of the potential bioenergy crops can be grown on marginal lands, are less nutrient and water demanding than food crops and they do not require active care, thus they require a much lower financial input than food crops, suggesting that abandoned lands have the potential to be used for bioenergy crop production. Recently, Campbell *et al.*[42] estimated that the global area of abandoned agricultural land ranges between 3.85 million and 4.72 million km^2, which is 7.8–9.6% of the total agricultural lands (crop and pasture), and which, on average, produce about 4.3 t/ha/y of biomass. The replacement of the growing biomass by high yielding bioenergy crops has the added potential of restoring economic value to these lands.

Studies on WSGs such as switchgrass show the important role of WSGs in improving soil properties and controlling erosion.[43] Tall WSGs consisting of tall grass species produce abundant above and below ground biomass, with extensive deep root systems that can improve soil physical properties (porosity, fluxes of water and air), soil chemical, and biological properties (organic carbon and water contents, microbial processes,), and ultimately maintain soil productivity. Many species of *Salix*, *Populus*, and *Miscanthus* have characteristics of 'pioneer' species that show adaptations for growth on poor sites and under harsh conditions. Available data indicate that herbaceous and woody plants can improve soil characteristics, reduce soil water and wind erosion, and sequester soil organic carbon. Because of their deep root systems, warm season grasses also promote long-term carbon sequestration in deeper soil profile unlike row crops.

Growing dedicated energy crops in marginal and abandoned lands instead of fertile lands used for food crops will further benefit the soil and environment. Warm season grasses can grow in nutrient-depleted, compacted, poorly drained, acid, and eroded soils, thus representing good candidates for reclamation of marginal lands.[30] For example, WSGs can grow and persist in adverse conditions including compact, poorly drained, acid, and relatively contaminated soils. Varvel *et al.*[44] showed that predicted ethanol yield from switchgrass grown in marginal soil was greater than that from corn stover under the same fertilization conditions, showing that dedicated energy crops can be a viable option for producing renewable energy on these lands. Plantations of SRWCs can also be used to restore degraded soil. On sandy and clayey soils, conversion of crop land to aspen (*Populus deltoides*) plantations improved soil water retention.[45] Soils planted with SRWCs retain more soil water than those under cultivation and SRWCs have much greater cumulative water infiltration than row crops and pasture.[33] It was actually shown that soil erosion loss from row crops areas was about ten times higher than that in areas planted with SRWCs.[46]

Some abandoned lands are created because of land degradation and erosion, which caused the lost of productivity, and are still subject of further degradation. Both WSGs and SRWCs can also control wind erosion. Switchgrass grows a tall rigid stem and has deep rooting systems that confer resistance to erosive forces of wind. Switchgrass was shown to be an effective barrier against wind in semiarid regions,[47] and as a drought-tolerant species it can grow well in sandy and relatively windy environments. WSGs can be grown to control wind erosion near the soil surface,[48] especially in semiarid regions where wind erosion is more damaging than water erosion for soils. As a conclusion, WSGs have the capacity to reduce water and wind erosion, whereas perennial WSGs provide a permanent defense against wind erosion over croplands.

2.5.2 Dry Lands

Deserts are not considered as biologically productive land since they are considered that they do not contribute to the human sustainability (FAO definition). The expansion of bioenergy crop production on desert area would have the benefit that it would not compete with land that could be used directly for food production. Deserts are also constantly expanding, thus development of tolerant perennial plantation that could prevent or reduce soil erosion by fixing the ground would have also a very positive impact. It is estimated at 2.6 million km^2 of lands that need irrigation to keep their production potential, which in a near future will become subject to desertification if nothing is done. Very often excessive irrigation generates salinity problems and water erosion that in longer term will reduce the vegetative cover that will amplify the erosion. It is estimated that an additional 14 million km^2 of lands is suffering from low desertification, which consequently become improper for food production if nothing is done to stop it.[10] The following discussion will be focusing on strategies that could use part of the desert to produce bioenergy biomass and on advantages of the development of new bioenergy crop lands to stop desertification and to restore degraded lands.

All dry lands cannot, unfortunately, be used for biomass production; however, hedges and lands in desertification process (lands that no longer support irrigation) could be primary targets. In warm and dry areas, there is a large competition between irrigation and drinkable water, which sometime creates water over drafting. In addition, it is commonly observed that over-irrigation in these hot areas increases salinity issues. Both, consequently, render the soil unsuitable for major food crop cultivation (productivity is too low) and stimulate erosion. The management of these areas by the plantation of dry tolerant species, has the potential of first reducing water consumption, of stopping the extension of desertification, possible land restoration, and to block sandy winds. Since these land types became non-sustainable for food production and therefore are, most of the time, abandoned, they are a potential target for bioenergy crop production.

Desertification is a huge worldwide problem and it is constantly expanding. It is not affecting only food production; it is also not providing carbon sequestration since biological activity is minimal. The main reason of desertification is caused by a loss of vegetation due to overgrazing, repetitive drought stresses or salinity, which consequently leaves the land susceptible to erosion. The reintroduction of plant species tolerant to drought and salt stresses and that are not or are poorly subject to grazing can stop the erosion, thus halting desertification. Also, by stopping erosion, especially wind erosion, which is responsible of sandstorms commonly observed in China, Australia, and Africa, it will improve air and water quality. The second advantage is that restoring plant growth on 'non-productive land', will increase carbon sequestration underground since plants will have to develop a large rooting system often associated with a microbial community.[49,50] The third positive aspect is that this vegetation will also regenerate a new litter fall, which will reintroduce organic matter in the ground, and which after few years will restore soil fertility,[51] increase water retention, and, in a long-term perspective, might restore lands for food production. In addition, the production of valuable biomass on lands which were sterile (or almost), will generate a new economical activity by creating new incomes for farmers and could potentially give energy independence to isolated areas. Therefore, it has the potential to improve living conditions of these poor areas.

The presence of cities located on desert borders should favor the sustainability of biomass production for bioenergy since this biomass conversion to energy could be integrated with city waste conversion (see the waste section).

The proximity should integrate the use of sewage water from the cities to generate a short-term irrigation strategy in order to help the establishment of perennial biofuel crop plantations.[52–54] A general observation is that nutrient deficiency is accruing in many arid areas and eroded lands mainly as nitrogen or phosphorus deficiency in North America, North Africa, and Australia.[55] These nutrient deficiencies may cause desertification but may also be caused by desertification. Any stresses reducing plant biomass productivity and perennity will generate losses of organic matter in the soil (reduction of supply) and will induce soil erosion. These nitrogen- and phosphorus-deficient lands will affect strongly the restoration of vegetation.[56] Thus, the plant selection will have a key role in the re-establishment of new vegetative covers dedicated for biofuels. Legume species have the capability to fix atmospheric nitrogen to supply to their own needs and to enrich their environment with nitrogen. Mycorrhiza extends the plant's ability to absorb water and nutrients, in particular phosphorus.

The integration of a temporal irrigation system with sewage water should help to establish new vegetative covers and could prevent plant losses during extended drought periods.[53,54] Sewage water is known to be rich in nutrients and is often directly released into rivers, lakes, or oceans, creating eutrophication.[57] The integration of temporal irrigation systems with sewage water would also have the advantage to clean up this used water. These bioenergy crop lands would create a kind of natural filter where plants would absorb most of nutrients before the water reaches underground water reserves and rivers. For food crop irrigation, this water is not very suitable[58] since it can potentially carry some pathogens[59] and various heavy metals that accumulate in various plant organs: fruits, seeds, and leaves.[60] The use of sewage water on bioenergy crop lands would stay at a very low level per plant since theses plants would have been selected to grow in dry areas. Therefore, the excess of water could be used to extend the amount of irrigated surfaces and the bioenergy crop land areas. However, the biomass that will have been irrigated with sewage water will have to be processed with caution to avoid any risk of pathogen proliferation, (i.e. in fermenters or gasifiers) and should therefore be preferentially thermo-converted into bioenergy instead of being bio-converted into biofuels.

To increase the potential success of restoring biomass-producing covers on arid and semi-arid areas to reverse desertification, plant selection will be very important and the use of plants already adapted to these extreme conditions should be the first target. These plants should be able to resist drought and salt stresses, cope with grazing, have low nutrient requirements, strong biofuel properties such as a good oil, latex, or sugar content, good above ground productivity, and low ash content. In the longer term these species or new species could be further genetically engineered to improve their bioenergy conversion efficiency and their stability under various desert stresses. Perennial species are the most suitable plants for this project since their rooting stems will help to fix the topsoil layer against erosion and they should not require too much labor. The invasiveness of the species will most likely be insignificant since these plants will be growing under extreme conditions. There are only very few studies focusing on the selection of plant species that could be used to stop the extension of the desert. These studies were poorly developed probably due to under funding and due to the absence of real economical driving forces. The development of desert-adapted energy crops and the demonstration of the advantages and its sustainability should stimulate this research due to the economical potential and the great potential impacts on human sustainability.

Mineral composition and pH will be also determinant factors for the plant selection since they will significantly affect plant growth and land restoration.[61] A few studies showed that the supply of mycorrhizae spores or rhizobium bacteria helped the establishment of perennial species.[62] In similar lines, the use of legume trees (such as smoke tree and mesquite) in nitrogen poor lands like the Sonoran desert (USA) could be used in a desert restoration program.[55] There are also a few studies on desert-adapted plants for their potential as bioenergy crops. The crassulacean acid metabolism (CAM) type plants, such as *Agave* and *Opuntia ficus-indica* are well adapted to semi-arid conditions and can produce large amounts of biomass up to 43t DM/ha/y.[63] In addition CAM plants such as *Agave* plants contain a large amount of sugar that can be directly used for fermentation.[64] From the Euphorbiaceae species, Jatropha plants are very well adapted to various stresses and can grow in semi-arid regions. They produce seeds that contain between 27 and 40% of oils, which rends it very attractive for biodiesel production.[65–67] Some trees such as *Moringa tinctoria* and *Acacia seyal* are know for their wood fuels value and are able to grow in arid and semiarid areas and are already grown in desert.[68,69] In China, sand willows are grown in desert areas to stop desert expansion and it also became a biomass source for bioenergy production.[70,71] There are several other perennial species from semi-arid areas that have been evaluated for their bioenergy potential such as biomass yield and oil content[71] suggesting that plant diversity should be available to avoid bioenergy crop monoculture and to target various arid and semi-arid areas.

In summary, research is progressing to identify several plant species that would have strong biofuel potential and that could be used to stop land erosion and desertification. Diversity of plant species has an important role in the sustainability of plant-based bioenergy production. In addition, soils properties and composition differ between deserts and within an area. It will require adapted species to increase the success of plant restoration in semi-arid and arid areas. The advantages of bringing biofuel crops into arid and semi-arid areas, is that they will not compete with the arable lands used for food production and, in the long term, there is the potential to restore some lands for food production in poor areas. Unfortunately, there is not enough information yet to perform a complete evaluation of the impact of arid and semi-arid land restoration. The potential to use desert plant grown biomass as a bioenergy resource still has to be further analyzed to estimate how much marginal arable land could be saved for food crops or diversity preservation. Finally, if part of the desert would become suitable to produce some bioenergy crops, this area will probably have to be reconsidered as biologically productive land since it would contribute to human sustainability.

2.5.3 Land Polluted with Heavy Metals and Other Contaminants

The rapid industrial development that occurred worldwide in recent years has raised land pollution and environmental issues. Elevated concentrations of heavy metals in soils represent potential long-term environmental and health concerns because of their persistence in the environment and their associated toxicity to biological organisms. Furthermore, the costs of soil remediation also represent financial issues to landowners since costs only, and not income, are associated with land restoration. Agricultural land contamination by arsenic mainly originated from mineral extraction and waste processes, which are caused by poultry and swine feed additives, pesticides, and highly soluble arsenic trioxide stockpiles.[72] The consequences of heavy metal accumulation in the soil are not only associated with the storage of toxic elements in plant organs growing on these polluted land, but also to ground water and river contamination due to leaching, and have the risk to render the land unable to support any plant growth.[73] For example, an estimated 36 million people in the Bengal Delta are at risk from drinking arsenic-contaminated water.[74] It is estimated that soils affected by pollution cover an area of 0.22 million km^2 worldwide, of which 0.09 million km^2 is located in Europe.

Heavy metals (including arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc) cannot be broken down into less harmful by-products, so phytoremediation strategies have been developed. They consist of using plants that can accumulate heavy metal in aboveground plant parts to remove them from the environment or to render them harmless.

High yielding biomass crops offer good potential for the phytoremediation of sites contaminated with heavy metals since it is not recommended to grow food crops on this land. This has the potential of creating financial income to restore polluted lands. Warm-season grasses and SRWCs can tolerate contaminated soils and be used as part of phytoremediation strategies.[75] Different biomass crops, species, and genotypes may show large differences in efficiency of heavy metal uptake, and in the concentration of metals in different plant parts. For phytoremediation purposes, it is desirable for metals to be concentrated in the harvested parts of the plant such as the stems or leaves of short rotation crops. For example the accumulation of pollutants in the leaves of SRWCs would allow a separation of leaf and stem organs and a processing of both organs into bioenergy independently. This separation would reduce the potential side effects of the pollutants in some conversion processes (bioconversion especially). Trees are now considered in phytoremediation strategies for heavy metal-contaminated lands.[76] In particular, willow (*Salix* spp.) encompasses characteristics required for both remediating and energy crops. Willow have been shown to take up large amounts of Cd and Zn. It can be propagated vegetatively and frequently harvested by coppicing, yielding as much as 10–15 t DM/ha/year. Bushy *Salix* species with erect stems, rapid growth, and good rooting ability are the most suitable for biomass coppice. In addition to high biomass productivity, *Salix* trees also have an effective nutrient uptake capacity and a pronounced capacity for heavy metal uptake, which allows them to colonize contaminated soils.[76] Recent studies also showed the ability for some poplar species to accumulate boron and selenium extracted from the soil,[77,78] as well as the potential for maize to remove zinc from moderately contaminated soils.[79] The contaminated nonfood biomass has a potential as a renewable energy source.[80,81] Thus, the generation of corn plants via genetic engineering that could be used for phytoremediation and that would not accumulate the pollutants into the seeds would have triple function: food, biofuels, and phytoremediation. Recent studies indicate that *Miscanthus* crops could be successfully grown on contaminated land, although high levels of heavy metals may reduce crop productivity. Most heavy metals accumulate in the roots and rhizomes, rather than in the harvested aerial parts.[82] In such a case, it would not be the ideal plant for phytoremediation since rhizomes removal would be required, but it still gives the option of growing bioenergy crops on contaminated lands.

Organic pollutants can often be converted by plants into less harmful metabolites. Research on hybrid poplars has demonstrated their ability to take up and effectively degrade or deactivate a number of contaminants, including atrazine, 1,4-dioxane, trinitrotoluene, and trichloroethylene.[83] Similarly, switchgrass tolerates soil contaminated with trinitrotoluene better than cool-season grasses such as tall fescue, and is effective at remediating soils contaminated with trinitrotoluene, atrazine, and metolachlor.[84–86]

Increasing plant tolerance and metabolism of organic chemicals or tolerance to heavy metals can be achieved using biotechnology. For example, plants can be engineered to absorb and metabolize higher amounts of metals and other pollutants by over-expressing modifying enzymes and transporters.[87,88] Understanding plant–microbe associations could also improve the efficiency of phytoremediation as many bacteria show a natural capacity to cope with contaminants.[89] A single genetically modified energy crop might be produced to efficiently take up several different pollutants, which would increase the effectiveness of phytoremediation of organic compounds and metals from contaminated sites, without impacting its biomass yield. It would offer the ability of using polluted lands, unsuitable for food crop production, to grow bioenergy crops with an economical value and to reduce environmental pollution via phytoremediation.

2.5.4 Saline Lands

Saline lands are estimated to represent 0.76 million km^2 worldwide, of which 0.53 million km^2 are present in Asia. Human-induced salinization can be the result of using irrigation water with 'high salt' content and mainly occurs under (semi-)arid conditions.[90] Salinization will also occur in coastal regions where seawater or fossil saline ground water intrudes on the ground water reserves of good quality used for irrigation. Human activities leading to an increase in evaporation of soil moisture in salt-containing soils can also induce salinization. The salinization of irrigated lands is increasingly detrimental to plant biomass production and agricultural productivity,[90,91] as most plant species are sensitive to high concentrations of sodium, which causes combined sodium toxicity and osmotic stress.

Thus salinity represents a significant land degradation and agricultural issue. For example, more than 50 % of the cropped land in Australia is affected by soil acidity, sodicity and salinity problems with an estimated annual impact to the agriculture of A$2,559 million.[92] No food-crops can be grown sustainably on this type of soil, which however represent available lands for halophyte plants, which can tolerate high salt levels. In particular, *Arundo donax* is a crop that produce high biomass yield (45 t DM/ha/y) on saline lands. Furthermore, this perennial rhizomatous grass does not produce pollen and does not have fertile seeds, making it a good candidate bioenergy crop.[93,94] More conventional bioenergy crops such as certain poplar clones were shown to produce biomass when irrigated with landfill leachate enriched in sodium and chloride.[95]

In addition, identifying genes implicated in salt stress response as well as sodium exporters offers strategies for improving salt resistance in plants using biotechnology. Genomic regions that influence salt tolerance were identified in monocot crop plants such as wheat and rice, and they correspond to transporters that mediate the intracellular concentrations of sodium and potassium.[96]

The development of plants tolerating high levels of salt could allow biomass production on saline lands – estimated at 200 000 to 300 000 acres in California – and could potentially be used for the recycling of sewage water for agricultural irrigation.[37]

2.6 Waste Biomass

Several million km^2 of lands are available today to produce dedicated biomass for bioenergy production. From the actual cultivated lands, several billion tonnes of organic matter/biomass are produced and consumed as food or material, but part of it, residues, is considered as waste since it cannot be used for food or for material production. Part of this waste is efficiently used to improve farming land quality or is recycled as valuable products. However, most of these organic residues are accumulated in landfills to produce CO_2 and pollute the water or are applied in excess on farming lands, which make them also useless and produce CO_2 and pollutants. The use of these residues can be considered as biomass produced on free land since the use of this biomass for bioenergy production will not compete with the food consumption. Their utilization has also the potential to be beneficial for the environment since it can reduce pollution. These wastes could be divided in several categories depending of their origin, whether they have been transformed or not, and if they contain undesirable chemicals or not. To simplify the evaluation, the residues will be presented according to their land origin: forestland residues, farmland residues, and city land residues.

2.6.1 Forest Land Residues

Residues generated from forestry have two origins: (i) forest management consisting of tree residues produced during the growth of the forest and (ii) from wood residues generated during wood harvest and processing. Tree residues correspond to leaves, needles, branches, and bark that falls on the ground during the forest growth. Wood harvest and processing generates branches, bark, sawdust, and pulping wastes. These timber wastes represent 68–76% of the total above ground biomass.[97–99] Only a small proportion of timber waste is utilized to produce energy, and it is estimated that approximately 50% of the forest biomass will be left in the forest for degradation[100] and the rest (18–26%) is generated from offsite processing. The total wood (round wood) consumption in 2008 was estimated at 3448.6 million m^3 and 45% of it (1556.7 million m^3) was designated for industrial use, the rest, the wood fuels, representing 1892.0 million m^3, was used as for energy production.[101,145] In 1998 it was estimated by FAO that approximately 56% of the industrial wood was used for construction, 24% for paper and paperboard, and 20% as processed wood.[102] Between bark, sawdust, and logging residues the density varies between 320 and 400 kg/m^3 with 50–55% moisture content.[103] With the estimation of 60% of timber waste and 0.350 tonnes/m^3 and 50% moisture, the available biomass left for degradation corresponds to approximately 905.25 million tonnes of DM every year ([3448.6/0.40]$\times$ [60%] $\times$ [0.35] $\times$ [50%]; [timber + timber wastes] $\times$ [percentage of timber wastes] $\times$ [density of timber wastes] $\times$ [moisture content]). It was estimated that 500 million tonnes of wood is yearly consumed during the last 10 years for paper krafting and pulping,[145] to produce approximately 225 million tonnes of pulp (pulping yield estimated at 45%)[104] and therefore 1575 million tonnes of waste called 'black liquor'.[105] This black liquor can be burned on site to produce energy and to recover chemicals and the energy excess sold out. Techno-economic model analysis suggests that a combination of techniques including black liquor gasification and 'black liquor gasification–combined cycle' have the potential to produce more energy than is consumed by the pulping industry.[106,107] These improvements would reclassify the fourth largest industrial energy consumer, the pulp and paper industry,[18] to that of a net energy producer.

Leaf litter would be an additional option to generate biomass for bioenergy production if well managed. Only a certain percentage should be harvested to avoid organic matter depletion and associated consequences such as nutrient depletion, erosion, and desertification. The approximate litter yields from leaves and barks generated in deciduous forest is estimated at 300 tonnes/km^2/year for forest aged between 20 and 90 years old in a cool temperate climate.[108–110] Interestingly, the difference of litter production between 'evergreen gymnosperm' and deciduous angiosperm is very little, but the main difference is that deciduous forest generate one main leaf fall a year, in contrast to a whole year 'leaf fall' in the gymnosperm forest.[108]

To reduce harvesting time and harvesting cost, managed deciduous forest should be the main target since tree distribution on the ground can be organized. Part of these managed forests are used to produce timbers designated for paper production, construction wood, or bioenergy, and according to the Forest Resource Assessment (FRA) 2005,[111] it represents 3% (1.18 million km^2) all forest lands. The use of leaf litter from these forests has the potential to generate approximately 70.8 billion tonnes/year with a 5-year harvesting cycle. Due to the absence of study on leaf litter removal an arbitrary 5-year harvest cycle has been selected. A 5-year cycle should have a low impact on the organic matter accumulation and it should be more cost-effective to reduce the number of harvests than a small yearly harvest. An additional advantage of harvesting leaf litter, bark, and branches, is that it will reduce the accumulation of potential fire hazard material, therefore it should reduce the propagation of wildfires.

In summary, the conversion of the entire wood industry waste has the potential to cover almost 11.4% (44.673×10^{18} J/year) of the yearly worldwide energetic consumption of fossil fuels; 19.915×10^{18} J/year from industrial wood residues (905.25 billion kg/year × 22 MJ/kg),[99] 23.625×10^{18} J/year from black liquor (1575 billion kg/year × 15 MJ)[112] and 1.133×10^{18} /year from litter falls (70.8 billion kg/year × 16 MJ).[99]

2.6.2 Farmland Residues

There are two main types of wastes generated on farmlands, straw residues and manures. Straw residues, stovers, are all generated from seed or sugar production, thus they will vary between countries, according to their main agricultural production. According to a study by Kim and Dale,[113] based on cropping surface and average yield between 1997 and 2001, 1387.7 million tonnes of straw and 180 million tonnes of bagasse would be available for bioenergy conversion. It corresponds to 751 million tonnes from rice straw, 354 million tonnes from wheat straw, 203.6 million tonnes from corn stover, 58 million tonnes from barley, 10.8 million tonnes of oat, 10.3 million tonnes of sorghum, and 180 million tonnes of sugarcane bagasse. In their study, they calculated that 60% land cover with straw residues are required to maintain the level of soil organic manure, and thus maintain the land quality.[114] The energy value stored in dry grass straw, corn stover, and bagasse is estimated to vary between 15.4 and 19.4[115] because of the variability in ash and carbon contents. The conversion into bioenergy of the entire grass-derived residues, minus the left over residue requirement for soil fertility maintenance, has the potential to feed 7% (27.3×10^{18} J/year) of the yearly worldwide energetic consumption derived from fossil fuels, using 17.4 MJ/kg as the energy content average per kg of dry biomass (1567.7 million tonnes × 17.4 MJ/kg).[115]

The second type of waste generated in large quantities from farming is manure. This is generated by intensive livestock production, mainly beef, swine, diary, and poultry to produce meat, milk, and eggs, designated for human nutrition. Part of it is efficiently used as fertilizer on crop fields, and the leftover is often applied in excess as fertilizer and therefore creates land, water, and air pollution. The land application is usually seasonal since part of the time the land is covered with crops, or the land is free but it is at the end of the growing season, and therefore the application would generate a lot of nutrient leaching during fall and winter time, thus causing water pollution.[116,117] One of the consequences is that manure needs to be stored between land utilization cycles, which also creates some pollution when effluents are not collected and due to CO_2 losses and the production of greenhouse gases caused by an anaerobic fermentation.

The energy value of manure produced by intensive farming was estimated at 1700 million tonnes/year in 1999, which represents approximately a total energy of 25.5×10^{18} J/year (1700 million tonnes/year × 15.5 GJ/tonne)[118] and which is equivalent to 6.5% of the yearly worldwide energetic consumption derived from fossil fuels. This percentage has to be interpreted with caution since it corresponds to 100% conversion of the manure into energy. In practice to keep the 'biofertilizer' value of the converted manure, only a part of the manure will be converted into energy. One of the common points between manure and the other farming residues is the organic content. In contrast the main differences are the water content which is very high in manure (except poultry manure) and the mineral composition (N, P, K, and many others) is very high, which render them not very suitable for thermo conversion or to conventional enzymatic hydrolysis (external supply of hydrolytic enzymes). The most efficient conversion system seems to be anaerobic digestion, which produces energy and biogas and reduces the amount of biomass and keeps an high nutrient availability in the residue, which can still, further on, be used as fertilizer and be applied on the fields.[119] There are several case studies that demonstrated the feasibility of manure conversion into biogas.[119–121] Some studies are also completed with mixed wastes consisting of mixing plant residues with the manures[122,123] or mixed with industrial organic residues[124] to improve the conversion efficiency into biogas.

2.6.3 Urban Land Residues

The surface covered by cities and diverse constructions represents approximately 3.5 million km^2 of land[125] in which city area is estimated around 0.75 million km^2.[126] In urban lands, the primary productivity is almost insignificant since most of it is covered by concrete, asphalt, and few personal gardens and small parks; however, these areas were able to generate more than 2.02 billion tonnes of solid waste worldwide in 2006, according to the Global Waste Management Market Assessment from 2007.[127] These residues are known as municipal/urban solid waste (MSW) and are largely composed of organic wastes and are mainly exported to and accumulated in landfills, as only a little fraction is recycled. The organic fraction of MSW is primarily composed of paper, cardboard wastes, green wastes (from garden and landscaping), and food waste derivatives. This biodegradable component represents approx. 50–70% of the MSW (i.e. 53% in USA, 48.9% in Spain, 46–64% in Asia).[128–130] One of the biggest issues with landfills is the generation of pollutants, and the organic fraction is one of the main contributors. This biomass is rich in minerals and heavy metals that are slowly released by microbes and leached by water to end up in the rivers and ground water when they are not drained up by specific collectors.[131,132] In addition, this biomass also contributes significantly to the production of greenhouse gas effects; it releases mostly methane and CO_2.[132–134] These gases are mainly generated from the lignocellulosic biomass (paper, cardboard wastes, cooking oils, and green wastes) composed of cellulose, hemicellulose, and lignin. As a result, the recycling of the lignocellulosic biomass would provide a great source material for bioenergy production, which would consequently reduce the emission of greenhouse gases and the amount of MSW, which is accumulated in landfills. Of course the recycling of plastics, and other recyclable materials, would also contribute significantly to the reduction of landfill pollution and could be used for energy production.

Several studies are focusing on the transformation of the MSW organic biomass into energy. Recently, Alle Zihao Shi and co-workers[135] reported that 82.9 billion liters of waste paper-based biofuels could be produced in the world. Wasted cooking oils consist of vegetable oils (corn peanut, sunflower, olive, and soybean), which after processing could be used as biodiesel.[136] Several methods have been already developed such as alkali-catalyzed transesterification, hydroprocessing, and enzymatic conversion to produce free fatty acids and fatty acid methyl esters.[137–139] Finally, there are also lots of food wastes derived from specific industrial processes such as grape and tomato skins and seeds.[140,141] Since the composition of this type of organic waste is well defined, specific bio- and thermo-conversion systems could be established to produce bioenergy. For example, 5 million tonnes of citrus peel are produced in Florida every year. Verma and co-workers[142] demonstrated that this biomass could be reused and transformed into ethanol after enzymatic hydrolysis and fermentation. In summary, the conversion of the entire biomass of MSW would generate 14×10^{18} J/year, and the incorporation of the non-biogenic fraction (i.e. plastics and rubber) would add an additional 11×10^{18} J/year, which represent 3.6% and 2.3% respectively or 5.9% of the yearly worldwide energetic consumption of fossil fuels.[143]

2.7 Conclusions

Worldwide energy consumption was estimated at 498×10^{18} J in 2006, from which 393×10^{18} J are originated from fossil fuels.[18] The importance of generating energy from photosynthetic organisms is to close the carbon cycle loop and reduce or stop carbon loading of the cycle with fossil fuels. In 2006, to replace the energy derived from fossil fuels, it would require the use of at least 28 million km^2 of the highest quality of marginal lands to produce the equivalent energy from plant biomass. Therefore, selecting and designing plants well adapted to marginal lands and with improved efficiency to harvest light and to fix CO_2 could achieve the reduced land requirements. Also the increase of the calorific value of the biomass as well as the efficiency of its conversion would reduce required surfaces to generate enough energy. For example, the lignin has a much higher calorific value than cellulose and hemicellulose (21.2 MJ/tonnes DM and 17.5 MJ/tonnes DM, respectively)[144] and represents only 25% of the biomass. The enrichment in oil content of the biomass without affecting plant yield would also increase the energetic values and could be used almost directly as liquid fuel after extraction. In addition to the calorific value of the biomass, a bidirectional adaptation of dedicated energy crops and conversion approaches will reduce drastically the energetic cost of conversion processes.

Another important aspect to consider is the conversion of organic wastes into energy. These 'leftovers' are already available from forest and wood processing, farm residues and wastes, and urban organic residues, and would fulfill 22.4% ($44.7 + 52.8 + 14 \times 10^{18}$ J) of the total worldwide energy consumption (498×10^{18} J), which consequently would reduce land needs by 22.4%. These organic wastes are converted into CO_2 naturally by biological conversion processes. The difference here is that with the same amount of CO_2 released into the atmosphere, some energy will be harvested and could potentially feed 20% of human energy consumption.

Growing bioenergy crops on non-food lands gives more than renewable energy. Increasing biomass production on marginal lands, degraded lands, and desert will also increase the accumulation of organic matter in the soil since biomass accumulations aboveground and below ground of plant organs are positively correlated. Thus, growing bioenergy crops on non-cultivated lands will also participate significantly in long-term carbon sequestration. Finally, since growing bioenergy crops will generate economical outcome, easy accessible polluted and eroded lands will become suitable to grow perennial plants for biomass, thus they can be used to either stop further erosion or help with phytoremediation. In a longer-term perspective, developing production of bioenergy crops could potentially restore to these areas the quality required to grow food crops again.

Acknowledgements

This work conducted by the Joint BioEnergy Institute was supported by the Office of Science, Office of Biological and Environmental Research, of the US Department of Energy under Contract No. DE-AC02-05CH11231.

References

1. I. N. Forseth, *in Nature Education Knowledge*, Nature Publishing Group, 2010, vol. 1.
2. *Terrestrial Global Productivity*, Academic Press, London, 2001.
3. T. C. Whitmore, *An Introduction to Tropical Rain Forests*, 2nd edn, Oxford University Press, Oxford, 1998.
4. D. Burslem, N. Garwood and S. Thomas, *Science*, 2001, **291**, 606.

5. J. Bruinsma, *World Agriculture: Towards 2015/2030: An FAO Perspective*, Earthscan Publications Ltd, London, 2003.
6. G. Fischer, S. Prieler and H. van Velthuizen, *Biomass and Bioenergy*, 2005, **28**, 119.
7. G. Daily, *Science*, 1995, **269**, 350.
8. K. Weibe and E. R. S. Resource Economics Division, *United States Department of Agriculture*, Economic Research Service, Washington, DC, Agricultural Economics Reports,2003.
9. P. L. G. Vlek, D. Hillel and A. K. Braimoh, *in Land Use and Soil Resources*, eds. A. K. Braimoh and P. L. G. Vlek, Springer Netherlands, 2008, pp. 1001–1119.
10. H. R. Eswaran, R. Lal and P. F. Reich, *Land Degradation: An Overview*, Oxford University Press, New Delhi, India, 2001.
11. H. Breman, *Biotropica*, 1992, **24**, 328.
12. J. Ibanez, J. Martinez and S. Schnabel, *Ecol. Model.*, 2007, **205**, 277.
13. H. Dregne, *Economic Geography*, 1977, **53**, 9.
14. F. Chapin and G. Shaver, *Ecology*, 1985, **66**, 564.
15. A. McGuire, J. Melillo, D. Kicklighter, Y. Pan, X. Xiao, J. Helfrich, B. Moore, C. Vorosmarty and A. Schloss, *Global Biogeochemical Cycles*, 1997, **11**, 173.
16. X. Xiao, D. Kicklighter, J. Melillo, A. McGuire, P. H. Stone and A. P. Sokolov, *Responses of Primary Production and Total Carbon Storage to Changes in Climate and Atmospheric* CO_2 *Concentration*, Massachusetts Institute of Technology, Cambridge, Massachusetts,1995.
17. R. Fuentes and C. Taliaferro, in *Trends in New Crops and New Uses*, eds. J. Janick and A. Whipkey, ASHS Press, Alexandria, VA, 2002, p. 599.
18. IEA-Report, *Key World Energy Statistics*, International Energy Agency, Paris, France, 2008.
19. R. C. Francis, R. B. Hanna, S.-J. Shin, A. F. Brown and D. E. Riemenschneider, *Biomass and Bioenergy*, 2006, **30**, 803.
20. B. Greaves, N. Borralho and C. Raymond, *Forest Science*, 1997, **43**, 465.
21. N. D. Kien, T. H. Quang, G. Jansson, C. Harwood, D. Clapham and S. von Arnold, *Annals of Forest Science*, 2009, **66**, 711.
22. M. Lindstrom, H. Jameel, V. Naithani, A. Kirkman and J. Renard, in *Materials, Chemicals, and Energy from Forest Biomass*, ed. D. S. Argyropoulos, Oxford University Press, 2007, p. 613.
23. C. Walter, S. Carson, M. Menzies, T. Richardson and M. Carson, *World Journal of Microbiology and Biotechnology*, 1998, **14**, 321.
24. J. S. Yuan, K. H. Tiller, H. Al-Ahmad, N. R. Stewart and C. N. Stewart, *Trends Plant Sci.*, 2008, **13**, 421.
25. X.-G. Zhu, S. P. Long and D. R. Ort, *Annu. Rev. Plant Biol.*, 2010, **61**, 235.
26. S. Gan and R. M. Amasino, *Science*, 1995, **270**, 1986.
27. R. K. M. Hay and J. Roy Porter, *The Physiology of Crop Yield*, 2nd edn, Wiley-Blackwell, 2006.
28. O. Calderini, T. Bovone, C. Scotti, F. Pupilli, E. Piano and S. Arcioni, *Plant Cell Rep.*, 2007, **26**, 611.

29. P. R. H. Robson, I. S. Donnison, K. Wang, B. Frame, S. E. Pegg, A. Thomas and H. Thomas, *Plant Biotechnol. J.*, 2004, **2**, 101.
30. H. Blanco-Canqui, *Agronomy J.*, 2010, **102**, 403.
31. M. Sanderson, R. Reed, S. McLaughlin, S. Wullschleger, B. Conger, D. Parrish, D. Wolf, C. Taliaferro, A. Hopkins, W. Ocumpaugh, M. Hussey, J. Read and C. Tischler, *Bioresour. Technol.*, 1996, **56**, 83.
32. R. Miller and B. A. Bender, in *Proceedings of the Short Rotation Crops International Conference*, eds. J. R. S. Zalensy, R. Mitchell and J. Richardson, USDA Forest Service, Northern Research Station, Bloomington, Minnesota, 2008, p. 36.
33. L. Bharati, K. Lee, T. Isenhart and R. Schultz, *Agroforestry Systems*, 2002, **56**, 249.
34. M. D. Coleman, J. G. Isebrands, D. N. Tolsted and V. R. Tolbert, *J. Environ Manag.*, 2004, **33**, S299.
35. A. H. Heggenstaller, R. P. Anex, M. Liebman, D. N. Sundberg and L. R. Gibson, *Agronomy J.*, 2008, **100**, 1740.
36. E. Malezieux, Y. Crozat, C. Dupraz, M. Laurans, D. Makowski, H. Ozier-Lafontaine, B. Rapidel, S. de Tourdonnet and M. Valantin-Morison, *Agronomy for Sustainable Development*, 2009, **29**, 43.
37. D. Putnam, *38th California Alfalfa & Forage Symposium and Western Alfalfa Seed Conference*, UC-Davis California, USA, 2008.
38. G. Pilate, E. Guiney, K. Holt, M. Petit-Conil, C. Lapierre, J.-C. Leplé, B. Pollet, I. Mila, E. A. Webster, H. G. Marstorp, D. W. Hopkins, L. Jouanin, W. Boerjan, W. Schuch, D. Cornu and C. Halpin, *Nature Biotechnol.*, 2002, **20**, 607.
39. Y. Xi, Y. Ge and Z. Wang, *Methods Mol. Biol.*, 2009, **581**, 53.
40. M. G. S. Fernandez, P. W. Becraft, Y. Yin and T. Luebberstedt, *Trends Plant Sci.*, 2009, **14**, 454.
41. L. R. Oldeman, R. T. A. Hakkeling and W. G. Sombroek, *World Map of the Status of Human-induced Soil Degradation: An Explanatory Note*, Global Assessment of Human-induced Soil Degradation (GLASOD), 1991.
42. J. E. Campbell, D. B. Lobell, R. C. Genova and C. B. Field, *Environ. Sci. Technol.*, 2008, **42**, 5791.
43. D. Kemper, S. Dabney, L. Kramer, D. Dominick and T. Keep, *J. Soil Water Conserv.*, 1992, **47**, 284.
44. G. E. Varvel, G. E. Vogel, R. B. Mitchell, R. F. Follett and J. M. Kimble, *Biomass Bioenergy*, 2008, **32**, 18.
45. I. Messing, A. Alriksson and W. Johansson, *Soil Use and Management*, 1997, **13**, 209.
46. D. Pimentel and J. Krummel, *Biomass*, 1987, **14**, 15.
47. J. Bilbro and D. Fryrear, *J. Soil Water Conserv.*, 1997, **52**, 447.
48. H. Blanco-Canqui and R. Lal, Principles of Soil Conservation and Management, *SpringerLink*, 2008.
49. V. Saul-Tcherkas and Y. Steinberger, *Soil Biol. Soil Biochem.*, 2009, **41**, 1882.

50. A. Porras-Alfaro, J. Herrera, R. L. Sinsabaugh, K. J. Odenbach, T. Lowrey and D. O. Natvig, *Appl. Environ. Microb.*, 2008, **74**, 2805.
51. S. A. Ewing, R. J. Southard, J. L. Macalady, A. S. Hartshorn and M. J. Johnson, *Soil Sci. Soc. Am. J.*, 2007, **71**, 469.
52. R. F. Daubenmire and H. E. Charter, *Botanical Gazette*, 1942, **103**, 762.
53. Y. A. Saadat, M. M. Jahromi and A. M. Hassanli, *World Appl. Sci. J.*, 2009, **7**, 1239.
54. G. Singh and M. Bhati, *J. Plant Nutr.*, 2003, **26**, 2469.
55. R. A. Virginia, in *Environmental Restoration: Science and Strategies for Restoring the Earth*, ed. J. J. Berger, Island Press, Washington DC, 1st edn, 1990, p. 412.
56. M. Bowker, J. Belnap, D. Davidson and S. Phillips, *Ecol. Appl.*, 2005, **15**, 1941.
57. P. J. Oberholster, A. M. Botha and T. E. Cloete, *Environ. Pollution*, 2008, **156**, 184.
58. O. Amahmid, S. Asmama and K. Bouhoum, *Int. J. Food Microbiol.*, 1999, **49**, 19.
59. K. Ibenyassine, R. A. Mhand, Y. Karamoko, B. Anajjar, M. Chouibani and M. M. Ennaji, *J. Environ. Health*, 2007, **69**, 47.
60. M. I. Lone, T. Mahmood, K. Saifullah and G. Hussain, *Int. J. Agric Biol.*, 2003, **5**, 533.
61. F. Huerta-Martinez, J. Vazquez-Garcia, E. Garcia-Moya, L. Lopez-Mata and H. Vaquera-Huerta, *Plant Ecol.*, 2004, **174**, 79.
62. N. Requena, E. Perez-Solis, C. Azcon-Aguilar, P. Jeffries and J. Barea, *Appl. Environ. Microb.*, 2001, **67**, 495.
63. P. Nobel, *New Phytologist*, 1991, **119**, 183.
64. A. M. Borland, H. Griffiths, J. Hartwell and J. A. C. Smith, *J. Exp. Bot.*, 2009, **60**, 2879.
65. L. Canoira, R. Alcantara, J. Garcia-Martinez and J. Carrasco, *Biomass and Bioenergy*, 2006, **30**, 76.
66. W. M. J. Achten, L. Verchot, Y. J. Franken, E. Mathijs, V. P. Singh, R. Aerts and B. Muys, *Biomass and Bioenergy*, 2008, **32**, 1063.
67. W. Achten, E. Mathijs, L. Verchot, V. Singh and R. Aerts, Biofuels, *Bioproducts & Biorefining*, 2007, **1**, 283.
68. M. Seth, *Bot. Rev.*, 2003, **69**, 321.
69. E. S. Ariga, *J. Sustainable Agric.*, 1997, **10**, 25.
70. OLGPSDS-report, *Review Sustainable Development in China – Agriculture, Rural Development, Land, Drought and Desertification*, The Office of the Leading Group for Promoting the Sustainable Development Strategy, P. R. China (Department of Regional Economy National Development and Reform Commission), 2008.
71. S. Xiong, Q.-G. Zhang, D.-Y. Zhang and R. Olsson, *Bioresour. Technol.*, 2008, **99**, 479.
72. T. F. Jones, *Poultry Sci.*, 2007, **86**, 2.

73. R. V. Galiulin, V. N. Bashkin, R. R. Galiulina and P. Birch, *Land Contamination & Reclamation*, 2001, **9**, 349.
74. D. K. Nordstrom, *Science*, 2002, **296**, 2143.
75. D.-H. Kang, L. Y. Hong, A. P. Schwab and M. K. Banks, *J. Environ. Sci. Health*, 2008, **43**, 627.
76. I. Pulford and C. Watson, *Environ. Int.*, 2003, **29**, 529.
77. G. Bañuelos, M. Shannon, H. Ajwa, J. H. Draper, J. Jordahl and L. Licht, *Int. J. Phytoremediation*, 1999, **1**, 81.
78. B. H. Robinson, S. R. Green, B. Chancerel, T. M. Mills and B. E. Clothier, *Environ. Pollution*, 2007, **150**, 225.
79. E. Meers, S. Van Slycken, K. Adriaensen, A. Ruttens, J. Vangronsveld, G. Du Laing, N. Witters, T. Thewys and F. M. G. Tack, *Chemosphere*, 2010, **78**, 35.
80. M. Ghosh and S. Singh, *Appl. Ecol. Environ. Res.*, 2005, **3**, 1.
81. N. Witters, S. V. Slycken, A. Ruttens, K. Adriaensen, E. Meers, L. Meiresonne, F. M. G. Tack, T. Thewys, E. Laes and J. Vangronsveld, *BioEnergy Res.*, 2009, **2**, 144.
82. B. Ezaki, E. Nagao, Y. Yamamoto, S. Nakashima and T. Enomoto, *Plant Cell Rep.*, 2008, **27**, 951.
83. J. Burken and J. Schnoor, *Environ. Sci. Technol.*, 1998, **32**, 3379.
84. G. Krishnan, G. Horst, S. Darnell and W. Powers, *Environ. Pollution*, 2000, **107**, 109.
85. T. Chekol, L. Vough and R. Chaney, *Int. J. Phytoremediation*, 2002, **4**, 17.
86. F. Zhao, E. Lombi and S. McGrath, *Plant and Soil*, 2003, **249**, 37.
87. D. N. Dowling and S. L. Doty, *Curr. Opin. Biotechnol.*, 2009, **20**, 204.
88. A. R. Memon and P. Schroder, *Environ. Sci. Pollution Res.*, 2009, **16**, 162.
89. N. Weyens, D. van der Lelie, S. Taghavi, L. Newman and J. Vangronsveld, *Trends Biotechnol.*, 2009, **27**, 591.
90. A. Banin and A. Fish, *Environ. Monitoring and Assessment*, 1995, **37**, 17.
91. J. S. Rawat and S. P. Banerjee, *Plant and Soil*, 1998, **205**, 163.
92. C. Williams, T. Biswas, G. Schrale and J. Virtue, Irrigation Australia 2008 Conference, *Melbourne*, 2008.
93. I. Lewandowski, J. Scurlock, E. Lindvall and M. Christou, *Biomass and Bioenergy*, 2003, **25**, 335.
94. W. F. Anderson, B. S. Dien, S. K. Brandon and J. D. Peterson, *Appl. Biochem. Biotechnol.*, 2008, **145**, 13.
95. J. A. Zalesny, R. S. Zalesny, A. H. Wiese, B. Sexton and R. B. Hall, *Environ. Pollution*, 2008, **155**, 72.
96. T. Horie, F. Hauser and J. I. Schroeder, *Trends Plant Sci.*, 2009, **14**, 660.
97. T. Abebe and S. Holm, *Int. For. Rev.*, 2003, **5**, 45.
98. T. Tahvanainen, H. Kilpeläinen, L. Sikanen, H. Heräjärvi, J. Lindblad and E. Verkasalo, *Wood Material Sci. Eng.*, 2008, **3**, 1.
99. J. Akarakiri, *Energy*, 1993, **18**, 763.
100. A. Demirbas, *Energy Sources*, 2009, **31**, 1687.

101. Z. Wenjun, *Environ. Monitoring and Assessment*, 2007, **125**, 301.
102. E. Matthews, *From Forests to Floorboards: Trends in Industrial Roundwood Production and Consumption*, EarthTrends 2001 World Resources Institute, 2001.
103. F. Wikstrom, *Biomass and Bioenergy*, 2007, **31**, 40.
104. A. Terdwongworakul, V. Punsuwan, W. Thanapase and S. Tsuchikawa, *J. Wood Sci.*, 2005, **51**, 167.
105. C. Biermann, *Essentials of Pulping and Papermaking*, Elsevier Science & Technology, San Diego, CA, 1993.
106. H. Eriksson and S. Harvey, *Energy*, 2004, **29**, 581.
107. S. Farahani, E. Worrell and G. Bryntse, Resources, *Conservation and Recycling*, 2004, **42**, 317.
108. J. Bray and E. Gorham, *Adv. Ecol. Res.*, 1964, **2**, 101.
109. R. M. Hurd, *Ecology*, 1971, **52**, 881.
110. A. Raizada and M. Srivastava, *Forest Ecology and Management*, 1986, **15**, 215.
111. FRA-Report, *Global Forest Resources Assessment 2005: 15 Key Findings*, Food and Agriculture Organization of the United Nations, Rome, Italy, 2005.
112. A. Demirbas, *Energy Conversion and Management*, 2002, **43**, 877.
113. S. Kim and B. Dale, *Biomass and Bioenergy*, 2004, **26**, 361.
114. W. W. Wilhelm, J. M. E. Johnson, D. L. Karlen and D. T. Lightle, *Agronomy J.*, 2007, **99**, 1665.
115. T. Tew and R. Cobill, in *Genetic Improvement of Bioenergy Crops*, ed. W. Vermerris, SpringerLink, New York, NY, 2008, p. 450.
116. R. Nicholson, J. Webb and A. Moore, *Biosystems Eng.*, 2002, **81**, 363.
117. H. Steinfeld and T. Wassenaar, *Annu. Rev. Environ. Res.*, 2007, **32**, 271.
118. J. Sheffield and H. Zygmunt, ed.*Department of Energy*, 1999.
119. K. B. Cantrell, T. Ducey, K. S. Ro and P. G. Hunt, *Bioresour. Technol.*, 2008, **99**, 7941.
120. S. R. Harper, C. C. Ross and G. E. Valentine, *J. Water Pollution Control Federation*, 1988, **60**, 876.
121. G. J. Escobar and M. A. Heikkilä, *Biogas Production in Farms*, Through Anaerobic Digestion of Cattle and Pig Manure. Case Studies and Research Activities in Europe, TEKES – the Finnish Funding Agency for Technology and Innovation, Länsi-Pasila, 1999.
122. R. Summers, P. Hobson, C. Harries and A. Richardson, *Biol. Wastes*, 1987, **20**, 43.
123. J. Lu, L. Zhu, G. Hu and J. Wu, *Biomass and Bioenergy*, 2010, **34**, 821.
124. E. Comino, M. Rosso and V. Riggio, *Bioresour. Technol.*, 2009, **100**, 5072.
125. CIESIN, Center for International Earth Science Information Network (CIESIN), International Food Policy Research Institute (IFPRI); Centro Internacional de Agricultura Tropical (CIAT). 2004. Global Rural-Urban Mapping Project (GRUMP), Socioeconomic Data and Applications Center (SEDAC), 2004 edn, 2005.
126. A. Schneider, M. A. Friedl and D. Potere, *Environ. Res. Lett.* 2009, 4, 0044003.

127. http://www.researchandmarkets.com/reportinfo.asp?report_id=461875, Global Waste Management Market Assessment 2007.
128. M. Kayhanian, *Waste Management Res.*, 1995, **13**, 123.
129. A. Garcia, M. Esteban, M. Marquez and P. Ramos, *Waste Management*, 2005, **25**, 780.
130. D. Hoornweg and L. Thomas, *What a Waste: Solid Waste Management in Asia*, Washington, DC, 1999.
131. D. Fatta, A. Papadopoulos and M. Loizidou, *Environ. Geochem. Health*, 1999, **21**, 175.
132. N. Wilson, L. Peissig, P. Burford, A. Radians, R. Burnyeat and B. Sielaff, *Land Treatment of Landfill Leachate*, Minnesota Pollution Control Agency, 2007.
133. J. Bogner and E. Mathews, *Global Biogeochem. Cycles*, 2003, **17**, 31.
134. X. F. Lou and J. Nair, *Bioresour. Technol.*, 2009, **100**, 3792.
135. A. Z. Shi, L. P. Koh and H. T. W. Tan, *Global Change Biology – Bioenergy*, 2009, **1**, 317.
136. Y. Zhang, M. A. Dube, D. D. McLean and M. Kates, *Bioresour. Technol.*, 2003, **90**, 229.
137. Z. Helwani, M. R. Othman, N. Aziz, W. J. N. Fernando and J. Kim, *Fuel Processing Technol.*, 2009, **90**, 1502.
138. C. Komintarachat and S. Chuepeng, *Ind. Eng. Chem. Res.*, 2009, **48**, 9350.
139. S. Bezergianni, A. Dimitriadis, A. Kalogianni and P. A. Pilavachi, *Bioresour. Technol.*, 2010, **101**, 6651.
140. R. Xu, L. Ferrante, C. Briens and F. Berruti, *J. Anal. Appl. Pyrolysis*, 2009, **86**, 58.
141. V. Mangut, E. Sabio, J. Ganan, J. Gonzalez, A. Ramiro, C. Gonzalez, S. Roman and A. Al-Kassir, *Fuel Processing Technol.*, 2006, **87**, 109.
142. D. Verma, A. Kanagaraj, S. Jin, N. D. Singh, P. E. Kolattukudy and H. Daniell, *Plant Biotechnol. J.*, 2010, **8**, 332.
143. E. I. A. (EIA), in *Energy Information Administration/Methodology for Allocating MSW to Biogenic/Non-Biogenic Energy*, ed. U. S. Department of Energy, Energy Information Administration, Washington DC, 2007.
144. E. S. Domalski and T. A. Milne, *Thermodynamic Data for Biomass Materials and Waste Components*, The American Society of Mechanical Engineers, New York, 1987.
145. http://faostat.fao.org