Sustainability **2015**, *7*, 8491-8521; doi:10.3390/su7078491

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Are Biofuels an Effective and Viable Energy Strategy for Industrialized Societies? A Reasoned Overview of Potentials and Limits

Tiziano Gomiero

Independent Consultant and Researcher on Multi-Criteria Farming and Food System Analysis, Agro-Energies, Environmental Issues, Treviso 30121, Italy; E-Mail: tiziano.gomiero@libero.it; Tel.: +39-32-0464-3496

Academic Editor: Andrew Kusiak

Received: 7 April 2015 / Accepted: 26 June 2015 / Published: 30 June 2015

Abstract: In this paper, I analyze the constraints that limit biomass from becoming an alternative, sustainable and efficient energy source, at least in relation to the current metabolism of developed countries. In order to be termed sustainable, the use of an energy source should be technically feasible, economically affordable and environmentally and socially viable, considering society as a whole. Above all, it should meet society's "metabolic needs," a fundamental issue that is overlooked in the mainstream biofuels narrative. The EROI (Energy Return on Investment) of biofuels reaches a few units, while the EROI of fossil fuels is 20–30 or higher and has a power density (W/m^2) thousands of times higher than the best biofuels, such as sugarcane in Brazil. When metabolic approaches are used it becomes clear that biomass cannot represent an energy carrier able to meet the metabolism of industrialized societies. For our industrial society to rely on "sustainable biofuels" for an important fraction of its energy, most of the agricultural and non-agricultural land would need to be used for crops, and at the same time a radical cut to our pattern of energy consumption would need to be implemented, whilst also achieving a significant population reduction.

Keywords: biofuels; carbon debt; climate change; energy efficiency; environmental impact; EROI; food security; GHGs; power density; societal metabolism

1. Biofuels: A New Old Idea for Old and New Problems

In the last decades, the idea of using biomass (especially when this is converted to liquid fuels, or biofuels) for sustainable energy production has been attracting more and more interest from policy makers, scientists and investors, in the hope of providing an answer to the energy crisis and to the need to reduce greenhouse gas (GHGs) emission. Biofuels are also believed to offer a new source of income to farmers and generate employment opportunities in rural areas, both in developed and developing countries.

Since the 1990s, the production of biofuels has been steadily increasing, mainly in the USA, Europe and Brazil, resulting in the processing of a large amount of crops: mainly maize and sugarcane to produce ethanol; and soybean, rapeseed and palm oil to produce biodiesel. In the USA, the 2003 Renewable Fuel Standard, and the 2007 Energy Security and Independence Act established a corn-ethanol production target of 56.8 billion liters by 2015, and a further target of 136 billion liters of ethanol for 2022, of which 80 billion should come from corn [1].

With the food price crisis hitting the world market of food commodities in 2007–2008, biofuels became a matter of international debate, as they were blamed as the cause of the problem [1]. Since then, the debate over biofuels has gained momentum, and ethical, socio-economic and environmental issues have begun to be widely discussed, both within the scientific community and in the wider society. Some scholars questioned the energy efficiency of biofuels, claiming that it was an unproductive enterprise (e.g., [2–13]), a point already made in the 1970s by energy experts such as Prof. David Pimentel (e.g., [2]), and Prof. Vaclav Smil (e.g., [4]). Biofuels, in fact, call for the adoption of those very same agricultural practices that for decades have been blamed for being highly energivorous and water consuming, and for contaminating the environment and threatening biodiversity and soil health [2–5,14–17].

Other works highlighted that, contrary to current belief, biofuel production may cause net CO_2 emission, in particular when tropical forests and pristine land are converted to plantations and crops for biofuel production. To express such a concept, the term “carbon debt” has been coined [18–20].

The interest in biofuel as a potential sustainable and renewable energy source is still high, as is attested by numerous scientific journals recently created in its name, and the number of funded research projects that focus on this topic. Private investments and public subsidies are still poured into this sector. Since the crisis, however, the focus shifted from first-generation biofuels (or the use of fuel crops) to second-generation biofuels, *i.e.*, the use of cellulosic ethanol (crop residues, woody biomass), and then to third-generation biofuels, *i.e.*, oil from algae.

To overcome the conflict over land use (food *vs.* fuel), it has been pointed out that using marginal land and non-crop species may be a solution—and non-crop species can indeed be used [21,22]. Important potential non-crop species are being considered, and the list includes: switchgrass (*Panicum virgatum* a perennial warm season grass native to North America), some species of the genus *Miscanthus* (from the family poaceae, a native of tropical and subtropical African regions and Southeast Asia), for their high growth rate and the possibility of growing them in poor soil, and the Jatropha genus (*Jatropha curcas*, an euforbiacea native of Central America, the seeds and nuts of which are toxic to humans, but have a high oil content, about 30%–40%). Palm oil (*Elaeis guineensis*, a species native of West and South-West Africa), is also becoming of high interest for the biofuel market. In this case, however, there is a risk that palm oil plantations may further increase the displacement of native forests in tropical countries (as happened for sugarcane plantations in Brazil), or replace other food crops, without providing any benefits to farmers. After the plantation is discontinued (20–25 years), the soil is then ruined and cannot easily serve for further agricultural activities.

International pressure drove the European Parliament's environmental committee, on February 2015, to agree that biofuel from food crops should not exceed 6% of final energy use in consumption in transport by 2020, and accept that changes in land use and the resulting emissions should be accounted for [23].

It has to be pointed out that in the EU there are still about 3 million ha cultivated with rapeseed (*Brassica napus*) to produce biodiesel, and part of the cereal production is used to produce ethanol. Furthermore, ethanol is also imported as an end product (about 0.8 Mtoe in 2010) mainly from Brazil, and biodiesel (either as end product or as feedstock) from soybean is brought in from Argentina and the USA. A smaller but growing share of biofuels is imported as crude palm oil from Indonesia and Malaysia (which produces about 90% of the world's palm oil) adding to the carbon debt [1]. The USA, notwithstanding the critics, converts nearly half of their corn production to ethanol [1]. The USA exports and imports sugarcane ethanol (the latter from Brazil), with figures that vary widely from year to year, due to the complex mix of market dynamics, determined by yearly production, market prices of agricultural commodities, subsidies and American laws about carbon intensity (which lead to a preference for Brazilian ethanol due its lower carbon intensity). In the last years, export has been on the rise: in 2013, the United States exported about 600 Mgallons (2271 Ml), of which about 40%–50% went to Canada, followed by Brazil and EU, whereas they imported about 300 Mgallons of ethanol (1135 Ml) from Brazil; in 2014, export reached 820 Mgallons (3104 Ml) while the import fell to 70 Mgallons (265 Ml) [24,25].

The debate on the sustainability of biofuels is still open, and many complex issues are at stake. In this study, I will review and synthetize the main issues involved in the current debate. I will analyze the constraints that limit biomass from becoming an alternative, sustainable and efficient energy source, at least in relation to the metabolism of developed countries at present. The aim is to offer a more comprehensive framing of the complexity of the issue, in the hope that researchers, and policy makers alike, may gain some new insights to improve their work on the assessment of biofuels.

In this paper, I argue that the sustainability of an energy source needs to be understood in relation to many different criteria and indicators, and to the scale of the analysis (which may differ according to different stakeholders). In order to be termed sustainable, the use of an energy source should be technically feasible, economically affordable, environmentally and socially viable, considering society as a whole (a solution that works in the lab microcosmos is a necessary but not sufficient condition). Above all, it should meet society's "metabolic needs" [4–7,12,26–29]. Using wood may seem a great idea for household heating, and it actually is in many rural areas, even in developed countries (and there are cases where wood energy plants seem to work, as in forest-rich areas of Canada, USA, and Norway). Nevertheless, that may not be a good (or a feasible) option in London, or New York, or to power a nation's heavy industry.

The paper is organized as follows. In Section 2, I discuss some concepts and indicators related to the assessment of energy efficiency, pointing out how the importance of some indicators is still underestimated. I stress the fact that different sorts of indicators are required in parallel to assess the quality of an energy source. In addition, the implications of the effect of scale and of system boundary definition are again another fundamental issue that I see is overlooked in the biofuels narrative. In Section 3, I discuss some issues concerning the role played by subsidies in sustaining the biofuel market, and a number of conflicts that can arise by the expansion of biofuels (e.g., food *vs.* fuel, food prices and land grabbing). In Section 4, I deal with the environmental impact of biofuels. Biofuels have been, and are, promoted on the basis that they help curb GHG emission. Some important studies refute this claim. Actually, there are indications that they may increase GHG emission. The case of palm oil for biodiesel production is discussed, as this culture is spreading in tropical countries, and may greatly affect the conservation of tropical forests. In Section 5, I discuss the pros and cons of the second generation of biofuels, *i.e.*, the use of lignocellulosic biomass (crop residues or woody material). In Section 6, I briefly discuss third-generation biofuels: algae. In Section 7, conclusions are drawn and warnings given along with some suggestions.

2. Energy Efficiency, Power, Social Metabolism and the Importance of Scale

The idea of transforming biomass in biofuels is not new. In the 1930s, in the USA, Henry Ford suggested using ethanol from corn to fuel his Model T. Critics are not new either. In the 1940s, in the USA, Samuel Brody, the pioneer of animal bioenergetics, claimed that biomass is a primary energy source of very low quality when compared with fossil fuels and remarked that "*it is said that we should use alcohol and vegetable oils after the petroleum energy has been exhausted. This reminds one of Marie Antoinette's advice to the Paris poor to eat cake when they had no bread*" [30] (p. 968). Biomass is still used as the main energy source by 2–3 billion people around the world, mostly in developing countries. For decades, Brazil and USA have been transforming part of their production of, respectively, sugarcane and corn into ethanol for their automobile fleet.

However, while the energetic consumption in developing countries is around 200–800 kg oil equivalents per capita per year, in developed countries, energy consumption ranges around 3000–4000 kg oil eq. per capita per year, with USA up to 7000 kg oil eq. [31]. In developed countries, there is a large percentage of peoplestill living in rural areas, and due to the relatively low income and cost of labor, biomass represents an efficient and economic energy source (in many cases the only one available). Industrialized societies are characterized by high-density urban areas, high incomes and high cost of labor requiring a much higher rate of energy consumption. This in turn requires relying on energy sources with a high-energy density, *i.e.*, with a high amount of energy stored per unit volume (MJ/L) or mass (MJ/kg). Energy needs to be supplied at a rate that matches and supports the high metabolism of these societies (the rate of energy consumption).

Developed countries are then characterized by allocating a small fraction of their working time to the energy production sector. This allows a reduction in the cost of energy (one of the most important objectives in order to achieve economic development), and to invest human working time in other productive activities, which guarantee a higher benefit.

2.1. Assessing Biofuels: The Necessity of a Multicriteria Approach

The proper assessment of an energy source, along with the energy transformation involved and the quality of the energy carriers, is a complex matter. Multiple qualitative and quantitative indicators across different scales of analysis have to be taken into account. Unfortunately, most present-day studies on energy assessment adopt a rather narrow focus. Life Cycle Analysis (LCA) is the most common tool, but, by its own nature, it does not allow for grasping and representing the underlying complexity of these processes [4,6,12,32].

Much research has been carried out concerning the energy efficiency and GHG emission profile of fuel crops. Findings from different experts, however, diverge considerably. Some authors claim that biofuels may represent an efficient alternative to oil, some of them referring to fuel crops, while others only refer to cellulosic ethanol. Other authors claim that biofuels and biomass in general are instead an inefficient alternative to fossil fuels. So, how is it possible that highly respected scholars can reach such opposing conclusions?

Ridley *et al.* [33] point out that, notwithstanding the large body of literature on this topic, still some important issues remain poorly explored, such as trade, biodiversity, and human health. The impacts of biofuels in the Southern Hemisphere is also poorly studied, compared to the Northern Hemisphere. This is a very important point, as it warns us that a bias may exist in the information we have, because of the fact that some issues have not yet been properly investigated. Ridley *et al.* [33] call for more interdisciplinary research to assess complex trade-offs and feedbacks inherent to an energy strategy with potential wide-reaching impacts.

Concerning the production of information, we have to face the fact that data-gathering systems rely on different approaches and methodologies, involving different focuses, models, assumptions and scale of analysis. To begin with, a major problem arises with the choice of system boundaries, the "boundary dilemma" as Smil [32] (p. 275) put it. The choices over where to make our system end can lead to large differences in the results [12,28,32]. Borrion *et al.* [34], in their extensive review of environmental LCA of lignocellulosic ethanol conversion, conclude that results strongly depend on system boundary, functional unit, data quality and allocation methods chosen. The authors also make an important remark stating that "*The lack of available data from commercial second generation ethanol plant and the uncertainties in technology performance have made the LCA study of the lignocellulosic ethanol conversion process particularly difficult and challenging*." [34] (p. 4648).

Thus, models tend to consider the adverse effects on food security, poverty, and GHG emissions driven by land-use change separately, and substantial differences exist with regards to the estimates of those effects [35]. This lack of integration, apart from making it difficult to properly assess the quality of the models, may also result in mistakes occurring in the course of data analysis and interpretation. A recent study by Searchinger *et al.* [35] found a major flaw in three important models used to set government policies in the United States and Europe. The authors found that in these models the GHG reduction supposedly provided by biofuels is in fact accountable for the reduction in food production. The models, in fact, fail to account that some of the crops diverted from food to biofuels are not replaced by planting crops elsewhere. Therefore, it is the reduction in food available for consumption, rather than any inherent fuel efficiency of biofuels, that explains the decline in CO_2 emissions in government models.

Assessments are scale dependent (and of course value laden, a matter which scientists often prefer not to confront). This means that before the assessment exercise takes place we have to frame properly the context in which we are operating. To put it simply, do cars pollute? It depends on how many cars we are talking about, the performance of their engines, their average speed, the quality of the fuel, *etc.* New "clean" engines on many new cars may cause more pollution than old dirty engines on few old cars; scale matters. But the scale has to be decided before carrying out the assessment. There is a very telling example concerning the calculation of biofuel efficiency presented by Shapouri *et al.* [36] *vs.* Giampietro *et al.* [26], on how to account for co-products. I quote [3] (p. 33) (Prof. David Pimentel was also a co-author of the paper [12]), as it is explained very clearly: "*Shapouri et al. reported a net energy* *return of 67% after including the co-products, primarily dried distillers grain (DDG) used to feed cattle. These co-products are not fuel! Giampietro* et al. *(1997) observed that although the by-product DDG may be considered as a positive output in the calculation of the output/input energy ratio in ethanol production, in a large-scale production of ethanol fuel, the DDG would be many times the commercial livestock feed needs each year in the U.S. (Giampietro* et al. *1997). It follows then that in a large-scale biofuel production, the DDG could become a serious waste disposal problem and increase the energy costs*." For more examples on how the scale issue matters, I refer the reader to [12,37].

Such issue of scale was also pointed out by Smil [4], in his assessment of the program PROALCOL, launched by the Brazilian government. Apart from a number of problems identified by Smil [4], (e.g., soil erosion, land conversion, productivity-related issues, economic viability), the author stressed that in order to achieve the production of ethanol from sugarcane forecast by the government, the process would have to also produce each year more than 150 million m^3 of *vinhoto*, the residue of the process. Such a byproduct can be dried up and used as feed, but that is a highly energy-intensive process. The liquid may be used as fertilizer, but it requires logistics for concentrating it, transporting it around the country, *etc.* So the usual solution is dumping the fluid into the nearest water bodies, and in that context, *vinhoto* is a very serious pollutant.

2.2. Assessing Energy Efficiency: How the Framing of the Issue Affects the Conclusions Drawn

Analyzing energy efficiency by assessing the Energy Return on Investment (EROI, or EROEI, the Energy Return on Energy Investment) of an energy source is more effective than relying on the earlier output/input analysis methodology, as it provides information on the net energy available to society (Figure 1). EROI refers to how much energy is returned from one unit of energy invested in an energy-producing activity [12,28,29], (see [27], for a review of the different approaches to the calculation).

The model developed by [12], and based on the earlier works of economist Nicolas Georgescu-Roegen [38,39], highlights the relationship that the process of making useful energy for society has with the structure and functioning of society itself. In this sense, it is important to distinguish "flows" from "funds." Giampietro and Mayumi [12] provide the following definitions: *Fund elements* are those that remain the same during analytical representation (they reflect the choice made by the analyst when deciding what the system is and what the system is made of); *Flow elements* are those that are either produced or consumed during analytical representation (they reflect the choice made by the analyst when deciding what the system does and how it interacts with its context). Flow elements can be described in terms of relevant monetary, energy and material flows.

Energy production does happen within a given context, and that context poses constraints to the functioning and performance of the energy production system. Energy flows (under their different forms), in order to happen, have to rely on services supplied by funds, which are structured to provide the, somewhat fixed, characteristics of the system (e.g., content of soil organic matter, working time available at the society level), relative to a certain timeframe.

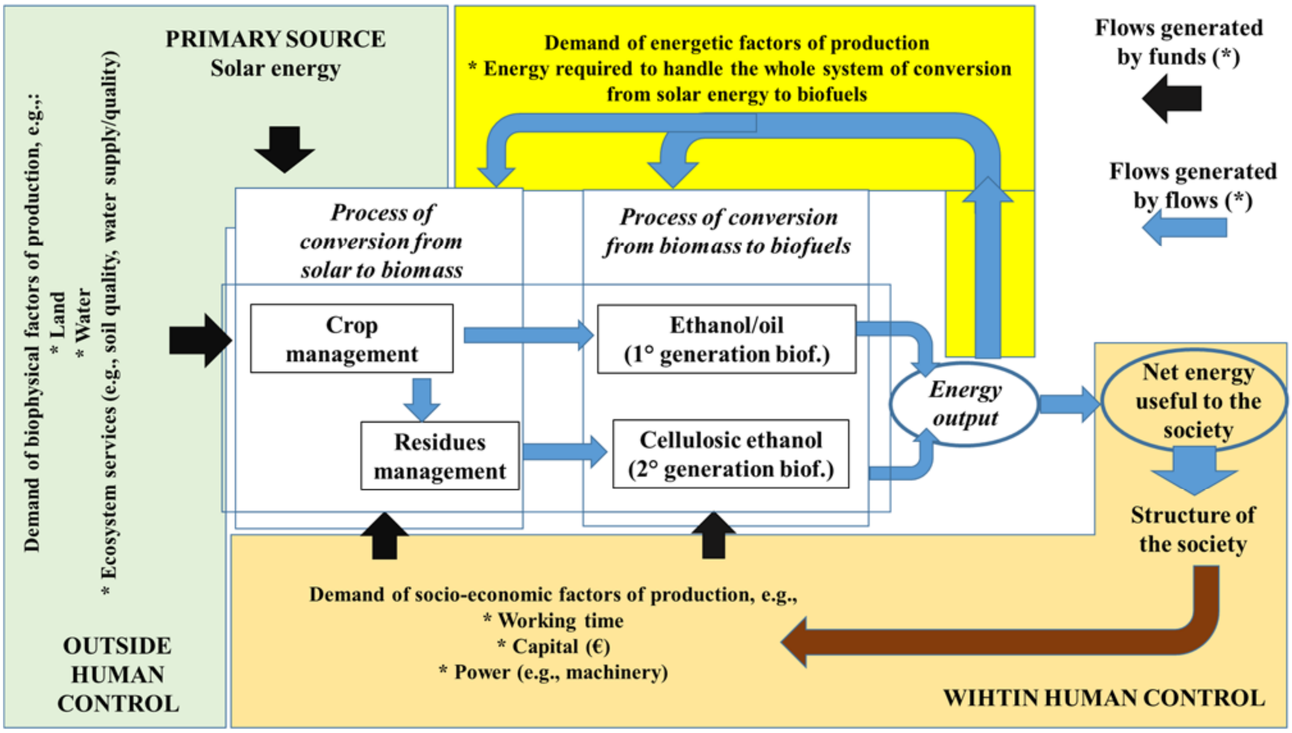

Figure 1. A model representing the relations between flows and funds for biofuel production. (*****) The flows generated by funds are flows that depend on the specific characteristics of energy generation (see text for explanations). (From [12], modified).

An important aspect that emerges from this representation is that the fund element must be preserved in order to sustain the flows. A reduction of soil organic matter (a fund element) affects crop production in many ways (e.g., reduced soil fertility and soil water availability, requirement of higher amount of inputs), leading to a reduction in productivity (the flow). A low amount of working time available (a fund) reduces the amount of activities a society can carry out (the flow).

On the energy analysis of biofuels, a fierce debate surrounds the issue of providing an accurate EROI estimate for biofuels, but this really has to do with a few decimals below or above one, as the EROI for biofuels is between 0.8 and 1.6, with sugarcane in Brazil as an outlier, reaching a top value of 8–10. This issue should not be a matter of concern, as fossil fuels, which fuel industrial societies, generate an EROI of 20–30 or more [12,27,29]. The fact that there are cases where biofuels can be produced at higher EROI does not really change the judgment over the low performance of biomass.

The fact is that we should adopt a different narrative and frame the discourse in a completely different way. A further and more important issue concerns, indeed, the problem of whether biomass can represent a suitable energy source able to fuel the metabolism of our industrialized societies. When addressing this issue, it emerges that we should refer to other indicators altogether; we need to adopt indicators relating to the level of power supply. Information about power levels, in fact, is fundamental to assess the viability of a metabolic process in relation to its internal constrains (funds), whereas information about the energy flow is important to assess the viability of a metabolic process in relation to external constraints (flows) [12,26]. The high metabolism of industrial societies requires a high power level, which in turn requires a concentrated flow of energy as input.

The power density of the energy source, that is to say the rate of energy flux per unit of area (W/m^2), is a key indicator [4–7]. Concerning power density, fossil fuels perform from 300 to 3000 times better than the best biofuel, such as sugarcane in Brazil (Table 1). See also Smil [7] (p. 265), for data about the power density of various kinds of biomass energy production.

Table 1. Power density of different power sources (after [7] modified).

Power Density (W/m^2)			
Power source	**Low**	**High**	**PD Nat. Gas (L & H)/PD other p.s. (H)**
Natural Gas	200	2000	-
Coal	100	1000	0.2–2
Solar (PV)	4	9	20–200
Solar (CSP)	4	10	20–200
Wind	0.5	1.5	130–1300
Biomass	0.5	0.6	330–3000

Legend: PD: Power Density; L: low; H: High.

We should also be aware of the quantity of energy required, and the working time that such an amount of energy demands upon society. In fact, the more time a society needs to allocate to the process of energy supply, the less time is available for other tasks and the higher the cost of energy. Giampietro and colleagues [12,26] argue that developed societies, in order to sustain their level of metabolism, require an energy throughput in the energy sector ranging from 10,000 to 20,000 MJ per hour of labor. The fact that the range of values achievable with biofuel are just 250–1600 MJ per hour of labor says it all. Of course, we may argue that this is a positive outcome, as it allows the creation of more jobs and reduce unemployment. Nevertheless, if wages in those jobs have to be comparable to those in other sectors of society, the cost of energy will skyrocket (I will comment again later on this issue).

Other indicators are also important and need to be taken into consideration (for reasons of space, here I have focused on the metabolic issue). On the biophysical side, one of these indicators is energy density. The final cost of energy in economic terms is, of course, another key issue. I will discuss that in Section 3.1, noting that biofuels can be produced only thanks to subsidies. A number of qualitative indicators are also highly relevant such as: the level of contamination produced, the reliability of the supply, and the level of risk involved [5–7,12,13,29].

It should be clear, therefore, that to perform a sound and effective assessment of an energy source is far from being a simple task, and requires the adoption of a number of different indicators related to different criteria and scales. The narrative about biofuels, instead, has been and still is, dangerously simplistic.

At present, the energetic discourse on biofuels is focused on the EROI, but, as we have seen, the EROI is just part of the story. The main problem with biofuels is that they have a power density that is simply too low and this requires handling an enormous quantity of biomass, costing society a lot of working time and capital. Those characteristics make biofuels unable to supply energy to match the metabolic rate of energy consumption of developed countries [5,6,12,26,32]. For our industrial society to rely on "sustainable biofuels" for an important fraction of its energy, it would require a complete reshaping of its metabolism:

- cropping most of the agricultural and non-agricultural land, affecting food supply and food affordability, increasing the impact on natural resources (water, soil health, pollution, loss of biodiversity);
- implementing an amazing occupational shift by sending millions of people back to the fields, which will increase the cost of energy (or at least drastically reduce the wages of those working in the sector);
- cutting our pattern of energy consumption, given the reduced flow of net energy;
- a consistent reduction of population size and consumption would be required;
- dealing with a continuous risk of running out of energy due to climate extremes, pests, *etc.*;
- such a massive amount of biomass may not be sustainable in the long term, and in the short run, it would require increasing amounts of input.

In summary, for a society (as for any living organism) the energetic supply is a matter of vital importance. The key factors being: (1) the quality of the energy source (fossil fuels are much better than biomass as most of the work has already been done by the Earth's ecosystems and geological forces over hundreds of millions of years); and (2) the overall efficiency of the supply process (extraction, transformation, *etc.*), that is to say, the net energy supplied to society at the proper rate of delivery, able to match the rate of energy demand. If the supply of energy cannot match the rate of metabolic energy consumption, society will reduce its metabolism accordingly.

3. First-Generation Biofuels: Subsidies, Food and Land Use

In this section, I review the role of subsidies in the sustainability of the biofuels market, and discuss the important impacts that biofuel policies have on food production, global food prices and land use.

3.1. Subsidies: Are They the Key for Biofuel Sustainability?

In the USA, where energy and agricultural policies supporting the transformation of corn into ethanol have been in force since the 1970s, the debate over the sustainability of biofuels is an old story (e.g., [2,40–43]. Lester Brown, although considering biofuels an option to be explored, already warned governments about "… *encouraging the production of alcohol fuel without inadvertently launching an industry that directly competes with food production*" [40] (p. 37). Brown poses also the ethical issue of whether the affluent car-owning minority from the developed world should use food crops to fuel their cars, driving up food prices and in turn reducing the margin of survival of the larger and poor majority in developing countries. Lockeretz [41], in his economic assessment of ethanol production from corn stoves (a work that can be considered a precursor to present-day environmental services analysis), highlights that the potential short-term benefits (in case it was possible to overcome the problems posed by ethanol extraction methodologies), could not secure long-term profits, and due to the loss of soil fertility, pose a risk even for food production. He also points out that policies on renewable energy, when failing to account for the whole, long-term costs and benefits, may result in wasting public money while harming the environment.

Other authors, such as Pimentel, Smil and Youngquist, were critical towards the real efficiency of biomass as an energy source, and posed important questions concerning its economic efficiency and environmental impact (e.g., soil, water, use of agrochemicals). Youngquist claims that ethanol policy in the USA is a mere political issue, with politicians granting subsidies for inefficient ethanol production in order to secure the votes from Corn Belt electors: "*The answer is that it is an example of politics overriding reason. The political block of the corn belt states holds votes crucial to elections, and companies which produce ethanol in the United States have been some of the largest contributors to political campaign funds in recent years*" [43] (pp. 243–244).

Subsidies are still the main driving force shaping biofuel policy and trade, and ultimately they keep all this going. Even with oil at 100US$/barrel, biofuels were still not competitive and needed subsidies (and that can also be expected, as a lot of fossil fuel is required to carry out intensive agriculture) [12,44,45]. Koplow and Steenblik [45], estimate that in 2008, in the USA, total support towards ethanol production ranged between 9.0 and 11.0 billion US$, with subsidies between 2009 and 2012 accounting for about 50% (up to 80% in 2007) of the ethanol market price. These figures are likely an underestimate, given the many faces economic support can take (from tax exemption to price premium), renderin precise subsidy assessment a difficult task [44,45].

According to the IEA, biofuel subsidies amounted to about US$22 billion in 2010, and are projected to increase to up to US$67 billion per year in 2035 [44]. Note that fossil fuel benefits from subsidies, too. Fossil-fuel subsidies are estimated at between US$45–75 billion a year in OECD countries and at US$409 billion in 2010 in non-OECD countries [44].

Some authors (e.g., [46]) back subsidy policy of biofuels on the basis that "*In any case, the size of the support of biofuels is small* (the authors are referring to the figure of US$ 20 billion they present earlier), *in relation to the cost of fossil fuel consumption subsidies amounted to $312 bn worldwide in 2009*". This reasoning is evidently flawed. The comparison refers to the total value, but has to be done on a per-unit basis instead. According to the BP Statistical Review of World Energy [47], in 2009 fossil fuel consumption amounted to about 10,000 Mt oil equivalent (3809 Mt oil, 2690 Mtoe gas, 3547 Mtoe coal), while biofuel amounted to about 52 Mt oil equivalent. Subsidies turn out to be 3.1 million US$ per Mt oil eq. in the case of fossil fuels (US$ 3/t), and 423 million US$ per Mt oil eq. in the case of biofuels (US$423/t), 136 times more. We may well wonder what are we doing with biofuels!

I do not believe that subsidies are *per se* a bad thing, and that they have to be dismantled in favor of a deregulated free market (as proposed by die-hard "free market" believers). In some cases, subsidies are very useful. They can act as catalytic trigger and spur a great leap forward. On the other, when a careful analysis of the real strategic opportunities and impacts is missing, subsidies can cause perverse distortions of the market and society, and become "perverse subsidies" [48], with many detrimental effects for all but those few who get the benefits [48,49]. Since the beginning, biofuels seem to fit the latter case [3,12,43–45,49].

But, who benefits most from these subsidies? In the USA, federal and state subsidies for ethanol production, that total more than US$7 per bushel of corn, have been always mainly paid to large corporations [9,45,49]. It thus seems that those who will gain from subsidies are large corporations that sell the fossil-fuel-derived inputs, and the losers are the farmers, the consumers and the tax payers! And the environment, of course.

Are we entering a perverse new biofuel lock-in, with tax payers in the north subsidizing the destruction of tropical ecosystems and the increase of world food prices, which will affect both people in developing countries as well as their own food bill? According to von Braun [50], Director General of the International Food Policy Research Institute in Washington D.C., to prevent the next international food crisis, among other things, actions have to be taken also concerning biofuels. Subsidies for biofuels, claims von Braun, have diverted funds from food and feed production, and should be removed.

3.2. Food vs. *Fuel: Who to Nourish?*

The biofuels issue became a matter of international debate along with the food price crisis in 2007–2008. Since early 2000, food prices have risen quickly. The International Monetary Fund's index of internationally traded food commodities prices increased by 130% from January 2002 to June 2008 and by 56% from January 2007 to June 2008 [51]. From January 2005 until June 2008, maize prices almost tripled, wheat prices increased by 127% and rice prices increased by 170%. The increase in grain prices was followed by increases in soybean, fats and oils prices, which doubled by mid-2006, notwithstanding the 2004/05 record crop production [51].

During the early months of 2008, international nominal prices of all major food commodities reached their highest level in nearly 50 years, while prices in real terms were the highest in nearly 30 years [51–54]. That resulted in soaring food prices, with dramatic consequences for poor people in the developing countries, particularly for those who spend most of their income on staple foods, driving, just in 2008, 110 million people into poverty, with 44 million added to the undernourished. Rioting and demonstrations took place in many cities around the world [1,52,55,56].

The increase in food prices has been accounted for according to a number of reasons such as: the reduction in the level of grain stocks, the increasing fuel costs, the increase in world population and the demand for food by China and India, weather-related production shortfalls and financial speculation; for a review see [57]. However, analyses were soon released by some international institutions (e.g., World Bank, the International Monetary Fund, FAO, United Nations), as well as other authors, ascribing to biofuels most of the weight of the problem [1,57]. Reports from the World Bank and the IMF concluded that rising biofuel production was responsible for the largest part of the jump in commodity prices and that this drove about 100 million people worldwide to be under the poverty line [51,53]. Biofuels diverted grain away from food towards fuel (with over a third of US corn used to produce ethanol and about half of vegetable oils in the EU going towards the production of biodiesel). Farmers were encouraged to set land aside for biofuel production. The situation sparked financial speculation in grains, quickly driving prices up. Some authors are less severe concerning the role played by biofuels in the crisis. Most of the analysts, however, agree that the biofuels played an important role in the matter [1,44,57]. Concerning the effect of the expansion of biofuel production, Alexandratos and Bruinsma [58] (p. 1) warn that: "*Should such trends continue, biofuels could prove to be a major disruptive force, possibly benefiting producers but harming low-income consumers*."

The future presents dramatic challenges. According to the UN [59], the human population will reach about 8 billion by 2030 and about 10 billion by 2050. Of these, 8 billion will be in developing countries. By 2030, worldwide, an additional 120 million ha—an area twice the size of France—will be needed to support food production [60], while built-up area/cropland area—estimated at 3.5% in 2000—will reach 5.1% (then 7% in 2050) [56].

Such a growth, unfortunately, pairs with other rather problematic trends [1,14,52,56,57,59,61–64]:

- crop productivity is stagnating and the yearly supply of grain per capita is decreasing;

- about 2 billion ha of the world's agricultural land have been degraded;
- the Human Appropriation of Net Primary Productivity (HANPP) reached 50% leaving less and less room and resources to biodiversity and ecosystems, thus compromising the existence of many species and the proper functioning of ecosystems.

Under these scary scenarios, we cannot see much room for devoting extensive areas to the production of "sustainable" biofuels, able to cover an important share of our energy consumption. Further to that, as the per capita income rose, consumers in developing countries not only increased per capita consumption of staple foods, they also diversified their diets to include more meat, dairy products and vegetable oils, which in turn amplified the demand for grains and oilseeds [52,56,58,63,64].

3.3. Land Concentration vs. Smallholders' Survival

In the last years, NGOs and international organizations, as well as experts on food security (e.g., [1,56,57,65–67]), have warned that the EU and USA biofuel policies are leading financial speculation to search for land in developing tropical countries to establish fuel crops to supply biofuels to the EU and USA. That may affect many millions of small farmers and indigenous people who are losing, or may lose, their land to large land holdings. Most sugarcane in Brazil, for instance, is cultivated where there once were tropical rainforests and the last native Guarani people. Such territory has already been greatly reduced (along with its native population) by cattle ranching. Thus further land conversion to sugarcane production will threaten what remains of the Amazon, its biodiversity and its people.

A land rush by big companies and governments in developing countries towards land conversion and planting fuel crops is already a reality. Countries such as Indonesia, Malaysia, Colombia, Brazil and Tanzania are already experiencing social conflicts. Cases are reported of small landowners and natives forced out from their land, workers exploited in plantations, and dwindling food security for the poor (e.g., [66–70]). Energy companies have stated that many African countries are good sources of biofuels, and have estimated that 30%–50% of their territory is suitable for fuel crops [71]. Are we seeing a new sort of "energetic colonialism," where northern developed countries are exploiting southern agroecosystems and labor to supply cheap bio-energy to their cars?

According to some authors, the biofuel market might potentially offer a way for poverty reduction and job creation, a market that can offer benefits to small farmers and supply cheap energy to local people. However, as the market is structured today, such a well-intentioned option may fail to work and the interests by the much stronger international corporations may prevail in taking advantage of the benefits coming from governmental subsidies and markets. At the same time, we cannot ignore that still 800 million people are considered to be undernourished [72]. Thankfully there has been a decrease from the 923 million estimated in 2007 [61], but we cannot forget that there are about 150 million people living at the borderline, for whom even a minor stress, such as a slight rise in food prices, or a reduced yield, may drive them to be undernourished.

3.4. Land Use: A Medium-Long-Term Perspective

When talking about sustainability we have to see things in perspective, in the medium and long run. In the near and distant future, we may run out of land. Agriculture and energy production are not the only activities competing for land. The population is competing for it too. More people means a demand for more land for urbanization, roads and other services.

Let us take a look at the USA as an example. The USA population, 310 million in 2009, will reach 440 million by 2050 (US Census Bureau, 2009). According to Nowak and Walton [73], the rate of rural land lost to development in the 1990s was about 0.4 million ha per year and the authors warn that if this rate continues until 2050, USA will have lost an additional 44 million ha of rural countryside. Such areas will be lost mostly at the expense of agriculture or conservative land programs. Brown [74] points out that the USA, with its 214 million motor vehicles, paved an estimated 16 million ha of land (in comparison to the 20 million ha that US farmers plant in wheat). About 13% of U.S. land area is currently dedicated to highways and urbanization, so adding other 150 million people will dramatically affect both the demand for food, as well as the demand for space (e.g., urbanization and highways). Considering future trends and competition for alternative land uses, Bindraban *et al.* [75] estimate that in Europe biofuel production will not be sustainable already by 2020.

4. Environmental Impact

The supposed environmental benefits provided by biofuels are the main arguments used by those advocating this energetic strategy, particularly referring to their potential for the abatement of GHG emissions and fossil fuel saving.

A more detailed analysis, however, indicates that in reality things turn out to be much more complex. The supposed environmental benefits seem much more limited than previously estimated. Actually, there are indications that, in some cases, biofuels exacerbate the situation. First-generation biofuels require the adoption of those very same intensive agricultural practices that had detrimental effects on the soil and the water table and increased contamination, *etc* in the first place. The use of crop residues may also affect soil health, and in any case requires increasing the use of inputs. When grassland and tropical land are converted to biofuel production (e.g., sugarcane, palm oil), net GHG emissions are generated. Therefore, for instance, EU energy policies, while aiming at reducing EU GHG emissions, may, in actual fact, be causing an overall net increase of those emissions.

4.1. Perpetuating the Detrimental Effects of Intensive Agriculture

For biofuels to substitute even a small fraction of the fossil fuels used at present, extensive and intensive agricultural practice have to be adopted, practices that are known to have a major impact on soil, water supply and biodiversity. The large use of agrochemicals, in turn, generates many kinds of pollution. Biofuels may end up exacerbating those problems [1,3,18,19,57,76]. It is noteworthy that the Human Appropriation of Net Primary Productivity (HANPP) has been estimated at about 50% [57,77]. Therefore, in order to reduce the impact of agricultural activities on natural resources, reduce contamination and prevent a major collapse of biodiversity at a global scale, there is a call for adopting farming practices that are more agroecological, which may preserve biodiversity-related ecosystem services [15,17,78–80].

Promoting the extensive cultivation of species suitable for biofuel production would increase two of the major causes of biodiversity loss on the planet, namely the clearing and conversion of yet more natural areas for monocultures, and the invasion by non-native species. The massive cultivation of foreign species, due to their suitability for the production of cellulosic ethanol (e.g., *Arundo donax*, "giant reed" or "giant cane") are posing a novel risk, that those species becoming invasive will displace indigenous ones and transform natural local environments [81–88]. Cultivating invasive species contradicts the warning provided by the International Union for Conservation of Nature, "*If the species is recorded as highly invasive under similar conditions (similar climate, and similar local ecosystems, and similar soil types), this species shall not be used*." [88] (p. 3).

4.2. "Carbon Debt": Biofuels and Increasing Carbon Emissions

The belief that burning biomass is carbon neutral has been questioned. Such an idea is founded upon the rather simplistic reasoning that CO_2 released in the burning is picked up again by plants, giving a net release of zero. There are a number of reasons why this is not so. Displacing tropical ecosystems in favor of plantations causes the loss of aboveground biomass, and also the release of a huge amount of carbon stored in the soil (about 50% of the total carbon in tropical forests is stored in the soil). Plantations will never store as much biomass as native ecosystems, and that leads to net carbon emissions. Converting grasslands into fuel crops will cause the net emission of the carbon stored in the native ecosystem. Even granting zero net emission to fuel crops, the stored carbon at time zero will still be lost, and added up to the atmosphere [18,19,77,87]. Some authors point out that also the model of carbon accounting used by IPCC suffers from this flaw. Haberl *et al.* [77] (p. 18) summarize the issue as follows: "… *burning biomass for energy provision increases the amount of carbon in the air just like burning coal, oil or gas if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces carbon sequestration. Neglecting this fact results in an accounting error that could be corrected by considering that only the use of 'additional biomass'—biomass from additional plant growth or biomass that would decompose rapidly if not used for bioenergy—can reduce carbon emissions. Failure to correct this accounting flaw will likely have substantial adverse consequences.*"

Estimates concerning the "carbon debt" (the carbon that is lost in land use change) have been already published (e.g., [18,19]:

- the conversion of rainforests, peatlands, savannas. Brazil and Southeast Asia may create a "biofuel carbon debt" by releasing 17 to 420 times more CO_2 than the annual GHGs reductions that these biofuels would provide by displacing fossil fuels;
- in the USA, corn-based ethanol will nearly double GHG emissions over 30 years, while cropping grasslands to produce biofuels (e.g., with switchgrass), will increase GHG emissions by 50%. Some USA public institutions concluded that much worse problems may be caused by fuel crops than by fossil fuels, due to corn ethanol and biodiesel made from soybean oil causing a large amount of land conversion to create a high "carbon debt" [88,89];

- in a meta-analysis carried out by Piñeiro *et al.* [90] on 142 soil studies, the authors conclude that soil C sequestered by setting aside former agricultural land was greater than the C credits generated by planting corn for ethanol on the same land for 40 years, and that C releases from the soil after planting corn for ethanol may, in some cases, completely offset C gains attributed to biofuel generation for at least 50 years. The authors, however, argue that if cellulosic ethanol was to become commercially available, cellulosic ethanol production from grassland could be an efficient alternative.

The problem of carbon debt is being openly addressed by many experts, who call for a revision of the policy on biofuels. The German Advisory Council on Global Change (WBGU), an independent scientific advisory body to the German Federal Government, stated that: "*WBGU is strictly opposed to the direct or indirect conversion of woodland, forests and wetlands into agricultural land for energy crops; such conversion is usually accompanied by non-compensable greenhouse gas emissions and its impacts on biological diversity and soil carbon storage are invariably negative*." [16] (p. 6). Recently, the IPCC pointed out that: "*…since for some biofuels indirect emissions—including from land use change—can lead to greater total emissions than when using petroleum products, policy support needs to be considered on a case by case basis*." [91] (p. 616).

4.3. The Case of "Oil Plantations" and the Fate of Tropical Ecosystems

The idea of "oil plantation" was already popular in the 1980s [43], and its implementation is showing unexpected and undesirable consequences. Gerasimchuk *et al.* [44], point out that exporting biofuels to heavily subsidized markets in the U.S. and Europe is a very attractive opportunity for biofuel producers in developing countries and generates a strong pressure towards land conversion to oil plantations, but this is achieved by converting existing crops and displacing native ecosystems. Oil plantations may provide a new market that can benefit both rich and poor countries. However, it has been noted that in many cases traders get most of the benefit. This has been the case particularly in a number of African and Latin American countries where foreign investors absorb the revenues from biofuel production and exports, without a considerable "trickle-down effect" on local communities [1,66,69].

European countries are currently producing biodiesel, relying mostly on locally grown oilseed rape. However, this is increasing the import of feedstocks from non-EU countries: crude palm oil imported from Indonesia and Malaysia, soybean from Argentina, and ethanol and pellets from USA and Canada [1,68].

The import of palm oil from Malaysia and Indonesia is under scrutiny and criticized for its potential impact on the remaining tropical forests [1,70].

In 2006, Indonesia had 4.1 million ha of oil palm plantation, 31% of the world's total, and this increased to about 7.2 million ha in 2010, accounting for 46% of the world's crude palm oil production. Malaysia is the regional leader in biodiesel production with an output of 540 million liters per annum as of 2009. Indonesia is second with the production of 400 million liters in 2010. By 2019, Indonesia and Malaysia are forecast to nearly double their production of biodiesel, respectively, and that may have a detrimental impact on local forests [1,70] (Figure 2).

(**a**) (**b**)

Figure 2. The effects of land use change in tropical ecosystems (**a**) tropical forest (source Wikipedia: http://en.wikipedia.org/wiki/Taman_Negara#mediaviewer/File:Taman-Negara.jpg); (**b**) palm oil plantation in Indonesia (from Wikipedia: http://en.wikipedia.org/wiki/Palm_oil).

The effect of international demand, however, may differ for different countries (e.g., [92]). According to Miyamoto *et al.* [93], in Malaysia, the oil palm area continued to expand from 1973 to 2010, but deforestation began to slow down from the mid-1980s, with oil palm planting shifting from newly cleared forest land to land that had been previously used for other agricultural commodities (e.g., rubber, coconut, cocoa) when they became less profitable than palm oil. The authors also found out that deforestation was linked with poverty reduction, and once the country moved to an industrialized and service economy, land clearing greatly reduced. The authors speculate that the demand for land decreased in the country due to the more attractive jobs created in other economic sectors of society. In Indonesia, over 50% of oil palm was planted from 2000 to 2010. By 2020, full lease development would convert 93,844 km^2 (about 90% of forested lands, including 41% of intact forests). Oil palm would then occupy 34% of lowlands outside protected areas [94]. As Indonesia is eight times more populated than Malaysia, and with a GDP per capita of only 30% of that of Malaysia, it is to be expected that the pressure for expansion of palm oil production will be much stronger in Indonesia (given also the dimension of the internal food and energy demand). Increasing global market demand for palm oil (which includes also the food, feed and industrial sector) may push many tropical developing countries to convert the usual food crops into palm oil production and that may lead to complex effects on local food security [1,66,67,69]. The conversion of the remaining native forests and ecosystems is another probable result. Given the doubtful environmental benefits provided by the biofuels, it is important for developed countries to rethink their energy policies regarding biofuels, in order to reduce their indirect impact (and responsibility) on tropical ecosystems.

It has been suggested that agricultural intensification may help reduce the expansion of plantations into pristine ecosystems. However, recent analysis found that using high-yielding oil palm crops to intensify productivity and then preserving the remaining biodiversity may not work either. Carrasco *et al.* [95], for example, argue that using high-yielding oil palm crops could actually lead to further tropical deforestation. That is because palm oil will become cheaper on the global food markets and will outcompete biofuels grown in temperate regions. That in turn will increase the planting of oil palm in tropical regions. In fact, paradoxically, while developed countries are claiming to import biofuels from tropical regions in order to reduce their CO_2 emission, they are actually contributing to an amplification of the problem, and concurring to fuel the process of tropical deforestation [18,19,44,96,97]. Houghton [98] warns that, between 1990 and 2010, forest degradation and deforestation accounted for 15% of anthropogenic carbon emissions and argues that we have to work to stop this trend. The author is rather critical about the international biofuel trade, which, he claims, is driven by distortions generated by the high subsidies in place in the USA and the EU, and is not going to work towards halting deforestation.

5. Second-Generation Biofuels

While the “first-generation” biofuels use food crops such as corn, rapeseed, palm and soybean, the “second-generation” fuels should be based on cellulosic material from plants, which could be grown without competing with crops, or coming from crop residues and other organic waste. Experts argue that cellulosic ethanol, if produced from low-input biomass grown on grassland, agriculturally marginal land or from waste biomass, could provide much greater energy supplies and environmental benefits than food-based biofuels [18,21,22,99]. Apparently, this may sound like a good idea. However, before launching into massive investments in this direction, some technical and ecological issues have to be properly analyzed and consequences addressed.

Concerning the use of crop residues, or “waste,” it must be pointed out that, in agroecosystems, as for ecosystems, “waste” does not exist [100–105]:

- crop residues play a major role in preserving soil fertility by supplying a source of organic matter and other elements that improve soil fertility. Harvesting all crop residues would pose a threat to agricultural ecosystems. Topsoil is being lost from land areas worldwide 10 to 40 times faster than the rate of soil renewal threatening soil fertility and future human food security [3,106]. A consistent harvest of crop residues as feedstock may result in worsening soil erosion rates from 10 up to 100-fold in critical areas [3], resulting in a disaster for agriculture. Corn residue removal in agroecosystems of the Corn Belt (USA) has greatly reduced corn yields and soil properties [100,103,104,107–109], leading also to an overall increase in GHG emissions [110] (Figure 3);
- a certain amount of residues (20%–30% and in some cases even more) can be harvested from the field without compromising soil fertility and increasing soil erosion [100,111–113]. However, nutrients have to be replaced by synthetic fertilizers [112]. Some experts (e.g., [104,107], state that, at present, we do not have a proper understanding about the sustainable amount of appropriation of crop residues, and that this depends on many factors (from soil characteristics to climate, from crops to the environment at large), so a precautionary approach has to be applied;
- agricultural soil, when properly managed, also plays an important role as a carbon sink. Lal [114] estimated that a strategic management of agricultural soil (e.g., reducing chemical inputs, moving from till to no-till farming, also known as *conservation tillage* or *zero tillage*, a way of growing crops from year to year without disturbing the soil by tillage, contrasting soil erosion and increasing soil organic matter), can sequester carbon at the rate of 500–1000 kg/ha/year in croplands, 50–500 kg/ha/year in grazing lands, 500–1000 kg/ha/year in forestlands and 5–10 kg/ha/year of pedogenic carbonates in arid lands [113]. The author points out that it has also the potential to offset fossil fuel emissions by 0.4 to 1.2 Gt C/year, that is to say 5% to 15% of the global emissions [102]. Furthermore, carbon in the soil offers many other valuable

environmental services. Evidence from numerous Long Term Agroecosystem Experiments indicates that returning residues to the soil rather than removing them converts many soils from "sources" to "sinks" for atmospheric CO_2 [103,105,113–115];

- the greater availability of crop residues and weed seeds translates to increased food supplies both for invertebrates and vertebrates, which play important ecological functions in agro-ecosystems, influencing, among other things: soil structure, nutrients cycling and water content, and the resistance and resilience against environmental stress and disturbance [57,115–120].

(**a**) (**b**)

Figure 3. (**a**) The removal of residues (here corn stover) leave the soil uncovered and at the mercy of the weather which quickly degrade it; (**b**) crop residues left on the soil guarantee soil protection against the effect of the weather, supply nutrition elements and help to preserve soil biodiversity and soil health (photos by the author).

Concerning the energy efficiency of this enterprise, at present, performances are much below those achieved by first-generation biofuels. That for a number of reasons:

- the complexity of the chemical processes involved in transforming lignocellulosic material to ethanol (or methanol); the large and complex infrastructures that are needed, and the economic investment required; the huge quantity of biomass required for a unit of fuel [2,4,6,7,9,10,121]. The arduousness of the challenge can be depicted by the continuous failure of experts' forecasts. In the early 1990s, it was forecast that in 10–15 years, a proper technology could be available to make cellulosic ethanol competitive. By the mid-2000s, experts were forecasting that in 10–15 years' time the major technical problems could be overcome. Present-day forecasts, again, are convinced the problems will be solved in 10–15 years [57,121]. However, as it is the case for first-generation biofuels, it seems that also for second-generation biofuels a large amount of public subsidies will be necessary to support this energy source, in order for it to be "competitive" [121];
- when compared to corn grain, it takes 2 to 5 times more cellulosic biomass to obtain the same amount of starch and sugars. This means that 2 to 5 times more biomass has to be produced and handled in order to obtain the same starches as for corn grain [9]. It is notable that, at present, only some pilot plants have been built to produce cellulosic ethanol and this thanks to a large amount of subsidies, though no where in the world are there commercial plants producing ethanol from cellulosic biomass, because it is neither energetically nor economically sound.

The point made by some early authors (e.g., [2–4]), holds true today. The total net contribution from converting agriculture residues into energy would be small when compared to the overall energy consumption (only 1% of the energy consumed as heat energy in the USA [2]) while the effect on soil ecology would be detrimental. A list of drawbacks is offered by [4] (p. 224): "*While crop residues can be a feedstock for any of the full array of biomass conversion technologies, the need for the easiest, cheapest, simplest route to transform such a minor, fluctuating, irregular, low density, poorly storable source of energy will largely limit the choice to combustion, certainly the most obvious method, and to anaerobic fermentation*".

Concerning converting grassland and prairie ecosystems to biofuel production, we face a series of other problems:

- Tilman *et al.* [21] suggest that all 235 million hectares of grassland available in the USA, plus crop residues, can be converted into cellulosic ethanol, recommending that crop residues, like corn stover, can be harvested and utilized as a fuel source. I have already mentioned residues; as for the use of grassland, this cannot be considered an empty space. There are tens of millions of livestock (cattle, sheep, and horses) grazing on that land, as well as all the wild fauna and flora living in those ecosystems [122];
- we should ask what are the real benefits of such massive land conversion. Converting those 235 million hectares of US grassland into ethanol, even using the optimistic conversion rate suggested by Tilman *et al.* [21], would still provide only 12% of the annual US consumption of oil and continuous harvesting will surely have a detrimental effect on nutrient cycling, soil erosion and soil ecology, leading to reduced productivity [122];
- what is missing altogether in this kind of analysis, however, is the assessment of the working time necessary to manage and handle such a vast surface and huge volume of biomass. Factoring this in will in turn greatly increase the projected cost of the fuel, unless wages are kept to a minimum, in a form of modern-day slavery.

On a global scale, again, there seems not to be that much free grassland to be converted to fuel production, at least without seriously compromising the life support systems of hundreds of millions of people. Herrero *et al.* [123] report that the livestock sector is the largest land-use system on Earth occupying 30% of the world's ice-free surface. It contributes to 40% of global agricultural GDP, providing an income for more than 1.3 billion people and the nourishment of at least 800 million food-insecure people.

6. Third-Generation: Algae

I wish to add a note concerning third generation biofuels, that is to say biofuels from oil produced by algae. A great deal of effort has recently been put into this enterprise (hundreds of million US$ within private investments and public subsidies). Algae present many advantages on both first and second-generation biofuels. They do not compete for food or land, can be fed on waste, and can grow anywhere where there is some water and sunlight. Some strains can harness 3% of the incoming sunlight as opposed to, at most, 1% for corn or sugarcane. Algae produce oil as reserve energy, and that oil can be extracted and used to produce biodiesel and it is believed they have a great potential to capture carbon [124,125]. According to Craig Venter's famous Synthetic Genomics, replacing all U.S.

transportation fuels with algal oil would take a farm roughly the size of Maryland (32,133 km^2), compared with an estimated farmland three times the size of the continental U.S. (3 * 9,629,091 km^2) for corn ethanol (in [125]).

This option, notwithstanding the huge investments and research programmes that go on since the early 1970s, is still failing to deliver, and there are no signs that we will have positive results any time soon. Actually, some energy analysts consider this "solution" so completely unrealistic that it should not even be worth any attention (e.g., [4,6,10,12]). Pimentel in his edited book on renewable energies [10], closes the work with chapter 20, on algae, consisting of two pages, summary and references included [126] (pp. 499–500). Pimentel claims that properly accounting for all the costs and assuming a realistic energy production level would lead to an estimated algal oil barrel cost of 800US$.

That the enterprise poses dramatic challenges is testified by a couple of telling facts. The U.S. National Renewable Energy Laboratory shut down its 18-year-old algal oil research program in 1996, after an investment of 25 million US$ in research funds. At present there are no companies that commercialize algal fuel, and the only one that did sold the fuel to the U.S. Navy at 424 US$ a gallon (100 US$ per liter) [125]. Actually, the companies making money on algae do so by selling the precious oil to the food and fashion industries as a nutritional supplement (as it is rich in omega-3 fatty acids) and beauty products [125,127]. Here, in brief, are some of the major problems faced by algal biofuels [4,5,6,16,125–128]:

- they shade one another and there are different levels of light saturation in the cultures;
- when grown in open ponds, algae can be affected by predators, disease and contamination by natural strains (and pounds consume a large amount of water through evaporation);
- growing algae inside bioreactors greatly increases the energy inputs and the cost of production;
- harvesting algae and separating the oil is a difficult and energy-intensive process;
- a key issue that limits the efficiency of algae for energy production is that oil production is the algae's defense against long periods without sunlight or nutrients. Then, in these conditions, algae grow slowly. That means that the maximum efficiency for oil production goes in parallel with poor plant growth. That plays against biomass productivity, and in turn limits overall biofuel production.

A different use of algae that has attracted much attention is photobiological H_2 production (bio-hydrogen can be obtained also by dark and photo-fermentation of organic materials by bacteria, in general, carbohydrates from organic waste) [129]. I discuss algae, as, at present, most of the research is focused on this sector, and because the issues concerning efficiency and performances are similar. The research on bio-hydrogen production began already in the mid-1990s. Tests are still limited to the lab, but according to some researchers, growing microalgae able to produce H_2 has great promise for generating large-scale sustainable energy (e.g. [130–134]). However, many technical limitations exist, hindering the exploitation of this potential resource (e.g., algal physiology, metabolic issues) [130,131]. Surely, further technical advances, such as genetic engineering, will help overcome some of these limitations [131]. Still, we face two major problems, the first concerning the scale issue. In lab conditions, experiments are carried out with "energy plants" consisting of a few milliliters, or at most, a few liters of algae, but real power plants consist of a thousand tons of water, and at this level, we face the problems listed above (algae shading one another, contamination, management *etc.*). The second problem relates to productivity, at two levels: (1) it is not enough to attain positive efficiency, efficiency has to be comparable to that achieved by fossil fuels (EROI of about 20:1 or higher); and (2) energy has to be supplied at a speed that matches society's metabolism. As with biodiesel, that does not imply that algae cannot play a role, in the future, as energy supply. What we need to know is how much lower is the performance of such an energy source compared to that of the fuels that are presently in use, as that will in turn affect our society's metabolism.

7. Conclusions

In this paper, I reviewed and discussed some key issues concerning the energetic, environmental and socio-economic sustainability of biofuels.

Food vs. fuels. First-generation biofuels have been shown to greatly affect food availability and the international market price of food commodities. There is a general agreement from both supporters and critics of biofuels that there is not enough land available to produce large amounts of fuel crops without causing a severe impact on global food commodities. Then, even allocating the entire USA cropland and grassland to biofuel production, the energy supply will account for only a small percentage of the USA energy consumption, and there are no hopes for biomass to cover an important share of USA energy demand; the same holds true for the EU.

Energy efficiency. Present-day energy assessments need to be improved. LCA has to be carefully undertaken to account for larger boundaries (especially when including biofuels trade). Different indicators of energy efficiency have to be employed at the same time (e.g., EROI, power density, power intensity). Societies are living systems, so energetic analysis has to be carried out adopting a metabolic approach. That is to say that we have to assess (1) whether the process of energy production is able to supply energy at a rate that matches the rate of energy consumption; and (2) how the functioning of society is affected by changes in the rate of energy supply and the specific characteristics of the energy source. Indicators such as LCA, Output/Input and EROI cannot provide this information. The EROI of biofuels reaches a few units (under the best estimates), while the EROI of fossil fuels is 20–30 or higher. More importantly, the latter have a power density thousands of times higher than the best biofuels such as sugarcane in Brazil. When metabolic approaches are used (e.g., [4,5,7,12,26]) it becomes clear that biomass cannot represent an energy carrier able to meet the metabolism of industrialized societies. It is simply too slow in delivering the energy. Large quantities of land, inputs (e.g., fertilizers, water, machinery), and volumes of biomass are required. That means that a large quantity of working time is required. In turn, that affects the cost of energy. For our industrial society to rely on "sustainable biofuels" for an important fraction of its energy, there would be a need to crop most of the agricultural and non-agricultural land, whilst implementing an amazing cut to our pattern of energy consumption and achieving a significant reduction in population. The problems are much worse in the case of second-generation biofuels, given the lower energy conversion efficiency, and the larger quantity of biomass needed per unit of net energy produced. The matter is even worse in the case of third generation biofuels, *i.e.*, algae.

Environmental impact. First generation biofuels rely on intensive agriculture. That means that they are going to exacerbate those environmental impacts that for decades have been addressed as major environmental issues. Subsidies can also make things worse as they incentivize the continuous cropping of a single culture—as is, for example, happening with maize in the USA—and this is going to represent a major agroecological risk. Second-generation biofuels may resolve the conflict with food production, but large-scale conversion of crop residues and agricultural waste into bioenergy may not be as energetically efficient (technical problems are far from solved), and will pose a major threat to long-term soil fertility and soil biodiversity. Converting prairies to cellulosic ethanol production may also not be viable with the present number of grazing livestock and the need to feed an ever-growing population. Some promising non-food species that are starting to be cropped in some countries are invasive species, and may turn out to cause major environmental damage in the future. It has long been claimed that biofuels can play an important role in reducing GHGs. Some experts already challenged such a claim decades ago. Moreover, recent works conclude that when the whole accounting is properly done, results indicate that biofuels may not help reduce GHG emissions. Conversely, extensive biofuel production may exacerbate GHG emissions and subsequently global warming, and increase the deforestation of tropical ecosystems.

Biofuel: a case of "perverse subsidies". Since the beginning, it was evident that biofuels could not compete with fossil fuels in the energy market. What keeps biofuels going is the large amount of public subsidies involved, and energy policies that impose blending a percentage of biofuels with gasoline. Subsidies concern also fossil fuels, but in the case of biofuels, the amount is much higher. Then, again, as it happens for agricultural activities, externalities are not accounted for (e.g., water depletion, soil fertility loss, pollution, carbon emissions). The increasing biofuel trade may also have detrimental effects of both ecosystems and the food system of the producers' countries, which in general are developing countries. Deeper and broader analyses are needed. The process of land grabbing, and other potential socio-economic conflicts should be carefully monitored as well. This might lead us to spend our hard-earned money more carefully. Subsidies should not be burned away to increase social and environmental problems. We can use them, for instance, to help farmers, both in developed and developing countries, to adopt energy-saving and environmentally friendly agricultural practices that can really help cut GHG emissions, prevent soil erosion, reduce water consumption, relieve the environment from toxic pollutants, preserve wild and domesticated biodiversity, and supply many other services. Again, subsidies could be used to explore different renewable energy sources, with a lower impact on our support systems, the soil and agroecosystems.

We know that biofuels cannot be our energy panacea, nor account for an even minimal share of energy supply to our society, without causing major social and environmental problems, undermining food security of billions of people and even resulting in worsening GHG emissions. In the near future, biomass should provide an ever-increasing amount of food, fiber, energy and ecosystem services for an increasing population, while at the same time the prediction is that significant stretches of land will be converted by urbanization, eroded away or lose their fertility, with their water resources depleted. Are we not asking a little too much from the planet? We should also have the courage to face two key issues: (1) we cannot keep increasing resource consumption and we need to change our lifestyle accordingly. In this sense, I cannot but agree with Smil [32] (p. 382) stating: "*I strongly believe that the key to managing future global energy needs is to break with the current expectation of unrestrained energy use in affluent societies.*"; and (2) we have to deal with population growth, we cannot expect to have 9–10 billion people inhabiting the Earth by 2050, without this representing a major impact on its support system.

The great ecologist H.T. Odum, in his book *Environment, Power and Society* (1971), pointed out that lab scientists were creating a "cruel illusion" (p. 125), by claiming that algae could feed the world [135].

Odum highlighted two major fallacies in the reasoning of lab workers. The first one concerns the fact that, although it is true that algae have high light conversion efficiency, that high efficiency is reached at low light intensity, and that in turn means reduced productivity. The second relies on considering algae free from their supporting ecological system, and failing to see that what can be done in a laboratory cannot be scaled up without facing major problems and new challenges.

We may reason whether, nearly 50 years after Odum's seminal work, too many technological hopes and too little understanding of ecology and of the complexity of living systems are leading our energivorous society, in its energetic despair, to a new "cruel illusion".

Acknowledgments

I thank Mario Giampietro, ICREA professor at the Universitat Autònoma de Barcelona, Spain, for his important insights on the energy efficiency issue, which helped me to grasp some key issues. I wish to thank Maurizio G. Paoletti, Dept. of Biology, Università di Padova, and David Pimentel, Cornell University, USA, with whom I had the pleasure to collaborate on this topic. I also wish to thank Lucio Marcello, Glasgow Biomedical Research Centre, University of Glasgow, for helping to edit the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. HLPE (High Level Panel of Experts). *Biofuels and Food Security*; A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security; FAO, Rome, Italy, 2013. Available online: http://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-5_Biofuels_and_food_security.pdf (accessed on 5 February 2015).
2. Pimentel, D.; Moran, M.A.; Fast, S.; Weber, G.; Bukantis, R.; Balliett, L.; Boveng, P.; Cleveland, C.; Hindman, S.; Young, M. Biomass energy from crop and forest residues. *Science* **1981**, *212*, 1110–1115.
3. Pimentel, D.; Patzek, T.; Cecil, G. Ethanol production: Energy, economic, and environmental losses. *Rev. Environ. Contam. Toxicol*. **2007**, *189*, 25–41.
4. Smil, V. *Biomass Energies*; Plenum Press: New York, NY, USA, 1983.
5. Smil, V. *Energy at the Crossroads*; The MIT Press: Cambridge, MA, USA, 2003.
6. Smil, V. *Energy: Myths and Realities*; The AEI Press: Washington, DC, USA, 2010.
7. Smil, V. Power Density Primer, 2010. Available online: http://www.vaclavsmil.com/wp-content/uploads/docs/smil-article-power-density-primer.pdf (accessed on 10 January 2015).
8. Ulgiati, S. A comprehensive energy and economic assessment of biofuels: When green is not enough. *Crit. Rev. Plant Sci.* **2001**, *20*, 71–106.
9. Pimentel, D.; Patzek, T. Ethanol production using corn, switchgrass, and wood: Biodiesel production using soybean and sunflower. *Nat. Resour. Res.* **2005**, *14*, 65–76.

10. Pimentel, D. (Ed.) *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*; Springer: New York, NY, USA, 2008.
11. Patzek, T. Thermodynamics of agricultural sustainability: The case of US maize agriculture. *Crit. Rev. Plant Sci.* **2008**, *27*, 272–293.
12. Giampietro, M.; Mayumi, K. *The Biofuel Delusion: The Fallacy of Large Scale Agro-Biofuels Production*; Earthscan: London, UK, 2009.
13. MacKay, D.J.C. *Sustainable Energy—Without the Hot Air*; UIT Cambridge Ltd.: Cambridge, UK 2009. Available online: http://www.withouthotair.com/download.html (accessed on 20 December 2014).
14. MEA (Millenium Ecosystem Assessment). *Ecosystems and Human Well-Being: Biodiversity Synthesis*; World Resources Institute: Washington, DC, USA, 2005. Available online: http://www.millenniumassessment.org/documents/document.354.aspx.pdf (accessed on 20 July 2014).
15. IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development). *Agriculture at the Crossroad*; Synthesis Report; Island Press: Washington, DC, USA, 2009. Available online: http://apps.unep.org/publications/pmtdocuments/-Agriculture%20at%20a%20crossroads%20-%20Synthesis%20report-2009Agriculture_at_ Crossroads_Synthesis_Report.pdf (accessed on 24 November 2014).
16. WBGU (German Advisory Council on Global Change). *Future Bioenergy and Sustainable Land Use*; Earthscan: London, UK, 2009. Available online: http://www.wbgu.de/fileadmin/templates/ dateien/veroeffentlichungen/hauptgutachten/jg2008/wbgu_jg2008_en.pdf (accessed on 20 July 2014).
17. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Is there a need for a more sustainable agriculture? *Crit. Rev. Plant Sci.* **2011**, *30*, 6–23.
18. Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1238.
19. Searchinger, T.D.; Hamburg, S.P.; Melillo, J.; Chameides, W.; Havlik, P.; Kammen, D.M.; Likens, G.E.; Lubowski, R.N.; Obersteiner, M.; Oppenheimer, M.; *et al.* Fixing a critical climate accounting error. *Science* **2009**, *326*, 527–528.
20. Robertson, G.P.; Dale, V.H.; Doering, O.C.; Hamburg, S.P.; Melillo, J.M.; Wander, M.M.; Parton, W.J.; Adler, P.R.; Barney, J.N.; Cruse, R.M.; *et al.* Sustainable biofuels redux. *Science* **2008**, *322*, 49–50.
21. Tilman, D.G.; Hill, J.M.; Lehman, C. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **2006**, *314*, 1598–1600.
22. Tilman, D.G.; Socolow, R.; Foley, J.A.; Hill, J.; Larson, E.; Lynd, L.; Pacala, S.; Reilly, J.; Searchinger, T.; Somerville, C.; *et al*. Beneficial biofuels—The food, energy, and environment trilemma. *Science* **2009**, *325*, 270–271.
23. EU (European Union). Environment Committee Backs Switchover to Advanced Biofuels. 2015. Available online: http://www.europarl.europa.eu/news/en/news-room/content/ 20150223IPR24714/html/Environment-Committee-backs-switchover-to-advanced-biofuels (accessed on 25 March 2015).

24. EIA (Energy Information Administration). U.S. Ethanol Exports in 2014 Reach Highest Level since 2011. Available online: http://www.eia.gov/todayinenergy/detail.cfm?id=20532 (accessed on 15 February 2015).
25. EIA (Energy Information Administration). U.S. Ethanol Imports from Brazil down in 2013. Available online: http://www.eia.gov/todayinenergy/detail.cfm?id=16131(accessed on 15 March 2015).
26. Giampietro, M.; Ulgiati, S.; Pimentel, D. Feasibility of large-scale biofuel production: Does an enlargement of scale change the picture? *BioScience* **1997**, *47*, 587–600.
27. Hall, C.A.S.; Lambert, J.G.; Balogh, S.B. EROI of different fuels and the implications for society. *Energy Policy* **2014**, *64*, 141–152.
28. Hall, C.A.S.; Dale, B.E.; Pimentel, D. Seeking to understand the reasons for different Energy Return on Investment (EROI) Estimates for Biofuels. *Sustainability* **2011**, *3*, 2413–2432.
29. Hall, C.A.S.; Cleveland, C.J.; Kaufmann, R. *Energy and Resource Quality*; Wiley-Interscience: New York, NY, USA, 1986.
30. Brody, S. *Bioenergetics and Growth*; Reinhold: New York, NY, USA, 1945.
31. World Bank, 2015. Energy Use (kg of Oil Equivalent Per Capita). Available online: http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE (accessed on 10 March 2015).
32. Smil, V. *Energy in Nature and Society: General Energetics of Complex Systems*; The MIT Press: Cambridge, MA, USA, 2008.
33. Ridley, C.E.; Clark, C.M.; LeDuc, S.D.; Bierwagen, B.G.; Lin, B.B.; Mehl, A.; Tobias, D.A. Biofuels: Network analysis of the literature reveals key environmental and economic unknowns. *Environ. Sci. Technol.* **2012**, *46*, 1309–1315.
34. Borrion, A.L.; McManus, M.C.; Hammond, G.P. Environmental life cycle assessment of lignocellulosic conversion to ethanol: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4638–4650.
35. Searchinger, T.; Edwards, R.; Mulligan, D.; Heimlich, R.; Plevin, R. Do biofuel policies seek to cut emissions by cutting food? *Science* **2015**, *15*, 1420–1422.
36. Shapouri, H.; Duffield, J.; McAloon, A.; Wang, M. *The 2001 Net Energy Balance of Corn-Ethanol (Preliminary)*; U.S. Department of Agriculture: Washington, DC, USA, 2004. Available online: http://www.biomassboard.gov/pdfs/net_energy_balanced.pdf (accessed on 10 March 2015).
37. Giampietro, M. *Multi-Scale Integrated Analysis of Agro-Ecosystems*; CRC Press: Boca Raton, FL, USA, 2004.
38. Georgescu-Roegen, N. Energy and economic myths. *Southern Econ. J.* **1975**, *41*, 347–381.
39. Georgescu-Roegen, N. *The Entropy Law and the Economic Process*; Harvard University Press: Cambridge, MA, USA, 1971.
40. Brown, L.R. Food or fuel: New Competition for the World's Cropland. Worldwatch Paper 35, Worldwatch Institute, Washington D.C., USA, 1980. Available online: http://www.fastonline.org/CD3WD_40/JF/424/19–414.pdf (accessed on 10 March 2014).
41. Lockeretz, W. Crop residues for energy: Comparative costs and benefits for the farmer, the energy facility, and the public. *Energy Agric*. **1981**, *1*, 71–89.
42. Pimentel, D. Ethanol fuels: Energy security economics and the environment. *J. Agric. Environ. Ethics* **1991**, *4*, 1–13.

43. Youngquist, W. *GeoDestinies: The Inevitable Control of Earth Resources over Nations and Individuals*; National Book Company: Portland, OR., USA, 1997.
44. Gerasimchuk, I.; Bridle, R.; Beaton, C.; Charles, C. State of Play on Biofuel Subsidies: Are Policies Ready to Shift? The International Institute for Sustainable Development, Winnipeg, Manitoba, Canada, 2012. Available online: http://www.iisd.org/gsi/sites/default/files/bf_stateplay_2012.pdf (accessed on 10 March 2015).
45. Koplow, D.; Steenblik, R. Subsidies o ethanol in the United States. In *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*; Pimentel, D., Ed.; Springer: Berlin, Germany; Heidelberg, Germany, 2008; pp. 79–108.
46. Valentine, J.; Clifton-Brown, J.; Hastings, A.; Robson, P.; Allison, G.; Smith, P. Food *vs.* fuel: The use of land for lignocellulosic "next generation" energy crops that minimize competition with primary food production. *GCB Bioenergy* **2012**, *4*, 1–19.
47. BP. Statistical Review of World Energy. 2015. Available online: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy/2013-in-review.html (accessed on 10 March 2015).
48. Myers, N.; Kent, J. *Perverse Subsidies: How Tax Dollars can Undercut the Environment and the Economy*; Island Press: Washington, DC, USA, 2001.
49. Peterson, E.W.F. *A Billion Dollars a Day: The Economics and Politics of Agricultural Subsidies*; Wiley-Blackwell: Hoboken, NJ, USA, 2009.
50. Von Braun, J. The food crisis isn't over. *Nature* **2008**, *456*, 701.
51. Mitchell, D. A Note on Rising Food Prices. The World Bank Development Prospects Group July 2008 Available online: http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2008/07/28/000020439_20080728103002/Rendered/PDF/WP4682.pdf (accessed on 17 July 2014).
52. FAO (Food and Agriculture Organization). Soaring Food Prices: Facts, Perspectives, Impacts and Actions Required. Available online: http://www.fao.org/fileadmin/user_upload/foodclimate/HLCdocs/HLC08-inf-1-E.pdf (accessed on 12 November 2014).
53. International Monetary Fund. Reaping the Benefits of Financial Globalization. 2007. Available online: http://www.imf.org/external/np/res/docs/2007/0607.htm (accessed on 20 July 2014).
54. Trostle, R. Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices. Available online: http://www.ers.usda.gov/PUBLICATIONS/WRS0801/WRS0801.PDF (accessed on 10 March 2015).
55. Gallagher, E. The Gallagher Review of the Indirect Effects of Biofuels Production. Available online: http://www.renewablefuelsagency.org/_db/_documents/Report_of_the_Gallagher_review.pdf (accessed on 5 March 2015).
56. UNEP (United Nations Environmental Programme). The Environmental Food Crisis the Environment's Role in Averting Future Food Crises a UNEP Rapid Response Assessment. Available online: http://www.grida.no (accessed on 10 February 2015).
57. Gomiero, T.; Paoletti, M.G.; Pimentel, D. Biofuels: Ethics and concern for the limits of human appropriation of ecosystem services. *J. Agric. Environ. Ethics* **2010**, *23*, 403–434.
58. Alexandratos, N.; Bruinsma, J. World Agriculture towards 2030/2050: The 2012 Revision. Available online: http://www.fao.org/docrep/016/ap106e/ap106e.pdf (accessed on 28 June 2015).

59. Bardgett, R.D.; van der Putten, V.H. Belowground biodiversity and ecosystem functioning. *Nature* **2014**, *515*, 505–551.
60. UN (United Nations). World Population Prospects: The 2012 Revision. Population Division, Department of Economic and Social Affairs, United Nations, New York, 2013. Available online: http://esa.un.org/wpp/Documentation/pdf/WPP2012_HIGHLIGHTS.pdf (accessed on 5 March 2015).
61. FAO (Food and Agriculture Organization). Global Agriculture towards 2050. High Level Expert Forum—How to Feed the World in 2050. Office of the Director, Agricultural Development Economics Division, FAO, Rome, 2009. Available online: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed on 10 February 2015).
62. FAO (Food and Agriculture Organization). The State of Food and Agriculture 2008. Available online: http://www.fao.org/docrep/011/i0100e/i0100e00.htm (accessed on 10 February 2009).
63. Montgomery, D.R. Soil erosion and agricultural sustainability. *PNAS* **2007**, *104*, 13268–13272.
64. Brown, L.R. *Outgrowing the Earth*; Earthscan: London, UK, 2005.
65. Smil, V. *Feeding the World: A Challenge for the Twenty-First Century*; MIT Press: Cambridge, MA, USA, 2008.
66. Eide, A. The Right to Food and the Impact of Liquid Biofuels (Agrofuels). http://www.fao.org/docrep/016/ap550e/ap550e.pdf (accessed on 10 February 2009).
67. ActionAid. Biofuels and Lad Grabs 2015. Available online: http://www.actionaid.org/eu/what-we-do/biofuels-and-land-grabs (accessed on 5 March 2015).
68. Oxfam. Biofuels. 2015. Available online: http://www.oxfam.org.uk/media-centre/press-releases/tag/biofuels (accessed on 5 March 2015).
69. Cotula, L.; Dyer, N.; Vermeulen, S. Fuelling exclusion? The Biofuels Boom and Poor People's Access to Land. International Institute for Environment and Development, London, UK, 2008. Available online: http://pubs.iied.org/pdfs/12551IIED.pdf (accessed on 10 February 2015).
70. Creutzig, F.; Corbera, E.; Bolwig, S.; Hunsberger, C. Integrating Place-Specific Livelihood and Equity Outcomes into Global Assessments of Bioenergy Deployment. *Environ. Res. Lett.* **2013**, *8*, doi:10.1088/1748-9326/8/3/035047.
71. Obidzinski, K.; Andriani, R.; Komarudin, H.; Andrianto, A. Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecol. Soc.* **2012**, *17*, Article 25.
72. Oxfam. Biofuelling Poverty—EU Plans Could be Disastrous for Poor People. Oxfam, 29 October 2007. Available online: http://www.oxfam.org/en/node/217 (accessed on 5 March 2015).
73. FAO; IFAD; and WFP. The State of Food Insecurity in the World 2014.Strengthening the Enabling Environment for Food Security and Nutrition. Available online: http://www.fao.org/3/a-i4030e.pdf (accessed on 5 March 2015).
74. Nowak, D.J.; Walton, J.T. Projected Urban Growth (2000–2050) and Its Estimated Impact on the US Forest Resource. Available online: http://www.fs.fed.us/ne/newtown_square/publications/other_publishers/OCR/ne_2005_nowak001.pdf (accessed on 10 February 2015).
75. Brown, L.R. Plan B: Rescuing a Planet under Stress and a Civilization in Trouble. Available online: http://www.earth-policy.org/Books/PB3/index.htm (accessed on 5 February 2015).

76. Bindraban, P.S.; Bulte, E.H.; Conijn, S.G. Can large-scale biofuels production be sustainable by 2020? *Agric. Syst.* **2009**, *101*, 197–199.
77. Crutzen, P.J.; Mosier, A.R.; Smith, K.A.; Winiwarter, W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys. Discuss*. **2007**, *7*, 11191–11205.
78. Haberl, H.; Sprinz, D.; Bonazountas, M.; Cocco, P.; Desaubies, Y.; Henze, M.; Hertel, O.; Johnson, R.K.; Kastrup, U.; Laconte, P.; *et al.* Correcting a fundamental error in green house gas accounting related to bioenergy. *Energy Policy* **2012**, *45*, 18–23.
79. Primack, R.B. *A Primer of Conservation Biology*, 4th ed.; Sinauer Associates: Sunderland, MA, USA, 2008.
80. Robertson, G.P.; Gross, K.L.; Hamilton, S.K.; Landis, D.A.; Schmidt, T.M.; Snapp, S.S.; Swinton, S.M. Farming for ecosystem services: An ecological approach to production agriculture. *Bioscience* **2012**, *64*, 404–415.
81. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental impact of different agricultural management practices: Conventional *vs.* organic agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124.
82. Cal-IPC. Arundo donax: Distribution and Impacts. California Invasive Plant Council, 2011. Available online: http://www.cal-ipc.org/ip/research/arundo/ (accessed on 10 March 2015).
83. Chapin, F.S., III; Zavaleta, E.S.; Eviner, V.T.; Naylor, R.L.; Vitousek, P.M.; Reynolds, H.L.; Hooper, D.U.; Lavorel, S.; Sala, O.E.; Hobbie, S.E.; *et al.* Consequences of changing biodiversity. *Nature* **2000**, *405*, 234–242.
84. GISP. Biofuel Run the Risk of Becoming Invasive Species. The Global Invasive Species Programme, May 2008. Available online: http://www.issg.org/pdf/publications/GISP/Resources/BiofuelsReport.pdf (accessed on 5 March 2015).
85. Smith, A.L.; Klenk, N.; Wood, S.; Hewitt, N.; Henriques, I.; Yana, N.; Bazely, D.R. Second generation biofuels and bioinvasions: An evaluation of invasive risks and policy responses in the United States and Canada. *Renew. Sustain. Energy Rev.* **2013**, *27*, 30–42.
86. Heikkinen, N.; ClimateWire. 49 plants that could make biofuel less troublesome. Available online: http://www.scientificamerican.com/article/49-plants-that-could-make-biofuel-less-troublesome/ (accessed on 2 February 2015).
87. IUCN (International Union for Conservation of Nature). Guidelines on Biofuels and Invasive Species. Available online: http://cmsdata.iucn.org/downloads/iucn_guidelines_on_biofuels_and_invasive_species_.pdf (accessed on 2 February 2015).
88. Searchinger, T.D. Biofuels and the need for additional carbon. *Environ. Res. Lett.* **2010**, *5*, 024007.
89. Babcock, B.A. Measuring Unmeasurable Land-Use Changes from Biofuels. Available online: http://www.card.iastate.edu/iowa_ag_review/summer_09/article2.aspx (accessed on 2 February 2015).
90. EPA (Environmental Protection Agency). Emissions from Land Use Change Due to Increased Biofuel Production—Satellite Imagery and Emissions Factor Analysis. Available online: http://www.epa.gov/OMS/renewablefuels/rfs2-peer-review-land-use.pdf (accessed on 10 February 2015).
91. Piñeiro, G.; Jobbágy, E.G.; Baker, J.; Murray, B.C.; Jackson, R.B. Set-asides can be better climate investment than corn ethanol. *Ecol. Appl.* **2009**, *19*, 277–282.

92. Sims R.; Schaeffer, R.; Creutzig, F.; Cruz-Núñez, X.; D'Agosto, M.; Dimitriu, D.; Figueroa Meza, M.J.; Fulton, L.; Kobayashi, S.; Lah, O.; *et al.* Transport. In *Climate Change 2014: Mitigation of Climate Change*. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., *et al.* Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 599–670.
93. Wicke, B.; Sikkema, R.; Dornburg, V.; Faaij, A. Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land Use Policy* **2011**, *28*, 193–206.
94. Miyamoto, M.; Parid, M.M.; Aini, Z.N.; Michinaka, T. Proximate and underlying causes of forest cover change in Peninsular Malaysia. *For. Policy Econ.* **2014**, *44*, 18–25.
95. Carlson, K.M.; Curran, L.M.; Asner, G.P.; McDonald Pittman, A.; Trigg, S.N.; Adeney, J.M. Carbon emissions from forest conversion by Kalimantan oil palm plantations. *Nat. Clim. Chang.* **2013**, *3*, 283–287.
96. Carrasco, L.R.; Larrosa, C.; Milner-Gulland, E.J.; Edwards, D.P. A double-edged sword for tropical forests. *Science* **2014**, *346*, 38–40.
97. Laurance, W.F.; Sayer, J.; Cassman, K.G. Agricultural expansion and its impacts on tropical nature. *TREE* **2014**, *29*, 107–116.
98. Wilcove, D.S.; Koh, L.P. Addressing the threats to biodiversity from oil-palm Agricultura. *Biodivers. Conserv*. **2010**, *19*, 999–1007.
99. Houghton, R.A. The emissions of carbon from deforestation and degradation in the tropics: Past trends and future potential. *Carbon Manag.* **2013**, *4*, 539–546.
100. Dwivedi, P.; Wang, W.; Hudiburg, T.; Jaiswal, D.; Parton, W.; Long, S.; DeLucia, E.; Khanna, M. Cost of abating Greenhouse Gas emissions with cellulosic ethanol. *Environ. Sci. Technol.* **2015**, *49*, 2512–2522.
101. Lindstrom, L.J. Effects of residue harvesting on water runoff, soil erosion and nutrient loss. *Agric. Ecosyst. Environ.* **1986**, *16*, 103–112.
102. Smil, V. Crop residues: Agriculture's largest harvest. *BioScience* **1999**, *49*, 299–308.
103. Lal, R. World crop residues production and implications of its use as a biofuel. *Environ. Int.* **2005**, *31*, 575–584.
104. Wilhelm, W.W.; Doran, J.W.; Power, J.F. Corn and soybean yield response to crop residue management under no-tillage production systems. *Agron. J.* **1986**, *78*, 184–189.
105. Wilhelm, W.W.; Johnson, J.M.F.; Karlen, D.L.; Lightle, D.T. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron. J.* **2007**, *99*, 1665–1667.
106. Rasmussen, P.E.; Goulding, K.W.T.; Brown, J.R.; Grace, P.R.; Janzen, H.H.; Körschens, M. Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science* **1998**, *282*, 893–896.
107. Pimentel, D.; Harvey, C.; Resosudarmo, P.; Sinclair, K.; Kurz, D.; McNair, M.; Crist, S.; Shpritz, L.; Fitton, L.; Saffouri, R.; *et al*. Environmental and economic costs of soil erosion and conservation benefits. *Science* **1995**, *267*, 1117–1123.
108. Blanco-Canqui, H.; Lal, R.; Post, W.P.; Owens, L.B. Changes in long-term no-till corn growth and yield under different rates of stover mulch. *Agron. J.* **2006**, *98*, 1128–1136.

109. Kenney, I.; Blanco-Canqui, H.; Presley, D.R.; Rice, C.W.; Janssen, K.; Olson, B. Soil and crop response to stover removal from rainfed and irrigated corn. *Glob. Chang. Biol. Bioenergy* **2014**, *7*, 219–230.
110. Linden, D.R.; Clapp, C.E.; Dowdy, R.H. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. *Soil Tillage Res.* **2000**, *56*, 167–174.
111. Liska, A.J.; Yang, H.; Milner, M.; Goddard, S.; Blanco-Canqui, H.; Pelton, M.P.; Fang, X.X.; Zhu, H.; Suyker, A.E. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. *Nat. Clim. Chang.* **2014**, *4*, 398–401.
112. Barber, S.A. Corn residue management and soil organic matter. *Agron. J.* **1979**, *71*, 625–627.
113. Karlen, D.L.; Hunt, P.G.; Campbell, R.B. Crop residue removal effects on corn yield and fertility of a Norfolk sandy loam. *Soil Sci. Soc. Am. J.* **1984**, *48*, 868–872.
114. Lal, R. Soil carbon management and climate change. *Carbon Manag.* **2014**, *4*, 439–462.
115. Lal, R. Carbon sequestration. *Philos. Trans. R. Soc. Lond. B Biol Sci*. **2008**, 27, Article 363.
116. Gomiero, T. Alternative land management strategies and their impact on soil conservation. *Agriculture* **2013**, *3*, 464–483.
117. Coleman, D.C.; Crossley, D.A., Jr.; Hendrix, P.F. *Fundamentals of Soil Ecology*, 2nd ed.; Academic Press: Amsterdam, The Netherlands, 2004.
118. Lavelle, P.; Spain, A.V. *Soil Ecology*; Kluwer: Amsterdam, The Netherlands, 2002.
119. Brussaard, L.; de Ruiter, P.C.; Brown, G.G. Soil biodiversity for agricultural sustainability. *Agric. Ecosyst. Environ.* **2007**, *121*, 233–244.
120. Heemsbergen, D.A.; Berg, M.P.; Loreau, M.; van Hal, J.R.; Faber, J.H.; Verhoef, H.A. Biodiversity effects on soil processes explained by interspecific functional dissimilarity. *Science* **2004**, *306*, 1019–1020.
121. Bardgett, R.; van der Putten, W.H. Belowground biodiversity and ecosystem functioning. *Nature* **2014**, *515*, 505–511.
122. Stephen, J.D.; Mabee, W.E.; Saddler, J.N. Will second-generation ethanol be able to compete with first-generation ethanol? Opportunities for cost reduction. *Biofuels Bioprod. Bioref.* **2011**, *6*, 159–176.
123. Pimentel, D.; Marklein, A.; Toth, M.A.; Karpoff, M.N.; Paul, G.S.; McCormack, R.; Kyriazis, J.; Krueger, T. Food Versus Biofuels: Environmental and Economic Costs. *Hum. Ecol.* **2009**, *37*, 1–12.
124. Herrero, M.; Havlík, P.; Valin, H.; Notenbaert, A.; Rufino, M.C.; Thornton, P.K.; Blümmel, M.; Weiss, F.; Grace, D.; Obersteiner, M. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *PNAS* **2013**, *110*, 20888–20893.
125. Sayre, R. Microalgae: The potential for carbon capture. *Bioscience* **2010**, *60*, 723–727.
126. Biello, D. Energy: The false promises of biofuels. *Sci. Am.* **2011**, *305*, 59–65.
127. Pimentel, D. A brief discussion on algae for oil production: Energy issues. In *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*; Pimentel, D., Ed.; Springer: New York, NY, USA, 2008; pp. 499–500.
128. La Monica, M. Why the Promise of Cheap Fuel from Super Bugs Fell Short. Available online: http://www.technologyreview.com/news/524011/why-the-promise-of-cheap-fuel-from-super-bugs-fell-short/ (accessed on 5 February 2015).

129. Xiao, N.; Chen, Y.; Chen, A.; Feng, L. Enhanced Bio-hydrogen production from protein wastewater by altering protein structure and amino acids acidification Type. *Sci. Rep.* **2014**, *4*, 3992, doi:10.1038/srep03992.
130. Ghirardi, M.L.; Posewitz, M.C.; Maness, P.C.; Dubini, A.; Yu, J.; Seibert, M. Hydrogenases and hydrogen photoproduction in oxygenic photosynthetic organisms. *Annu. Rev. Plant Biol.* **2007**, *58*, 71–91.
131. Volgusheva, A.; Styring, S.; Mamedov, F. Increased photosystem II stability promotes H2 production in sulfur-deprived *Chlamydomonas reinhardtii*. *PNAS* **2013**, *110*, 7223–7228.
132. Dubinic, A.; Ghirardi, M.L. Engineering photosynthetic organisms for the production of biohydrogen. *Photosynth Res.* **2015**, *123*, 241–253.
133. Hwang, J.-H.; Kim, H.-C.; Choi, J.-A.; Abou-Shanab, R.A.I.; Dempsey, B.A.; Regan, J.M.; Kim, J.R., Song, H.; Nam, I.-J.; Kim, S.-N.; *et al.* Photoautotrophic hydrogen production by eukaryotic microalgae under aerobic conditions. *Nat. Commun.* **2014**, doi:10.1038/ncomms4234.
134. Blankenship, R.; Tiede, D.; Barber, J.; Brudvig, G.; Fleming, G.; Ghirardi, M.; Gunner, M.; Junge, W.; Kramer, D.; Melis, A.; *et al.* Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement. *Science* **2011**, *332*, 805–809.
135. Odum, H.T. *Environment, Power, and Society*; WILEY: New York, NY, USA, 1971.