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**Review article**

# Grasslands for bioenergy production. A review

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**Abstract** – The promise of low-input high-diversity prairies to provide sustainable bioenergy production has recently been emphasized. This review article presents a critical discussion of some controversial points of using grasslands to produce bioenergy. The following issues are addressed: proteins versus biofuels; reactive nitrogen emissions; biodiversity; and effective land use. Two major disadvantages in deriving bioenergy from grasslands are identified: (i) marginal lands are displaced from their fundamental role of producing meat and milk foods, in contrast with the rising worldwide demand for high-quality food; and (ii) the combustion of N-rich grassland biomass, or by-products, results in emission of reactive N into the atmosphere and dramatically reduces the residence time of biologically-fixed nitrogen in the ecosystems. Nitrogen oxides, released during atmospheric combustion of fossil fuels and biomass, have a detrimental effect on global warming. Since intensively managed crops on fertile soils need to be cultivated to fulfil the dietary needs of populations, the potential role of inedible cereal crop residues in providing bioenergy merits consideration. This might spare more marginal land area for forage production or even for full natural use, in order to sustain high levels of biodiversity. Owing to the complexity of terrestrial systems, and the complexity of interactions, a modeling effort is needed in order to predict and quantify outcomes of specific combination of land use at higher integration levels.

**grassland / bioenergy / proteins vs. biofuel / reactive nitrogen emissions / biodiversity / effective land use**

## 1. INTRODUCTION

Plants have the unique ability to convert the incoming flux of solar energy, a renewable form of energy, into useful biomass, in the form of food, feed and fuel. However, in order to fully exploit the potential of crops for transforming solar energy into dry matter, crops need to be supplemented with fossil energy, either directly through soil tillage or pumping irrigation, or indirectly through the application of energy-intensive industrial fertilizers and pesticides (Pimentel, 1992). Consequently, modern agricultural systems are strongly dependent on fossil energy and therefore are vulnerable to the caprices of world fuel prices, and are also contributing to the rise in carbon dioxide ($CO_2$) and other greenhouse gases in the atmosphere (Mannion, 1997). Until the early 1900s, most of the energy used by human societies was derived from agriculture and forests. Even the first petrol and diesel engines were initially designed to run on ethanol and peanut oil, respectively (Collins and Duffield, 2005). From 1920 petroleum increasingly replaced vegetable oil, starch and cellulose as a feedstock for energy and industrial products (Morris and Ahmed, 1992). By the early 1970s, the energy crisis stimulated a renewed interest in producing energy from crop biomass. In addition, evidence indicates that this massive use of fossil energy has increased the concentration of $CO_2$ and other greenhouse gases in the Earth's atmosphere. This has also become a concern because of the potential long-term influence on global climate change (IPCC, 1996).

Some authors have concluded that the energy generated from plant biomass is close to "carbon neutral" because the $CO_2$ released in processing is the same as that captured by the plant by photosynthesis, while preserving the C stored for millenia in fossil reserves (Sims et al., 2006). In contrast, others have raised major ethical and environmental points: energy crops compete on fertile soil with food and feed production (Pimentel, 1991; Giampietro et al., 1997); and when natural land is converted into arable energy crops, increased pollution from fertilizers and pesticides, increased soil erosion, and decreased biodiversity can result (Pimentel, 2003).

Besides arable crops, grasslands can contribute to energy needs. Aiming to offset fossil fuels, prairie biomass can produce heat and electricity through direct combustion, or can be converted into transportation biofuels such as biodiesel, ethanol and methanol (Barnes and Nelson, 2003). Boylan et al. (2005) reported an encouraging pioneer experience of co-firing grasses (i.e., *Panicum virgatum* L., *Cynodon dactylon* L. Pers. and *Festuca spp*.) in an existing coal-fired plant: about 10% of the energy from biomass was successfully achieved. Recently, Tilman et al. (2006) and Hill (2007) reported intriguing results on biofuel derived from low-input high-diversity grassland. In essence, a well-balanced mixture of 16 native prairie plant species, including C3 and C4 grasses, legumes, forbs and woody species, produced 238% more aboveground biomass than plots sowed to a single species. The net energy gain (i.e., output–input) for conversion of biomass into electricity, ethanol and synfuel was very close to that of maize (*Zea mays* L.) grain converted into ethanol, with major gains

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on output to input ratios. The basic strategies underlying their experiment are the following:

- use of legumes as a primary route of nitrogen in the ecosystems, in order to avoid the use of the fossil energy-intensive industrial nitrogen fertilizers;
- use of a diverse range of native prairie plant species to gain high efficiency in exploiting light, water and nutrient resources, and to achieve stability in yields.

In emphasizing the outcomes of their experiment (conducted in Cedar Creek, Minnesota, USA), they pointed out that biofuel derived from low-input high-diversity grassland neither displaces food production nor causes loss of biodiversity. In this review, I present a critical analysis of some controversial issues regarding the use of prairies for producing renewable energy. In particular, I pose a deliberately provocative question: it is worthwhile to displace forages from their traditional role of feeding animals, and consequently mankind, for the purpose of producing energy? To address this question, the following issues are discussed: (i) proteins versus biofuel; (ii) reactive nitrogen emissions; (iii) biodiversity; and (iv) effective use of land resources: intensification vs. extensification.

## 2. PROTEINS VERSUS BIOFUEL

*"The primary form of food is grass. Grass feeds the ox: the ox nourishes man: man dies and goes back to grass again; and so the tide of life, with everlasting repetition, in continuous circles, moves endlessly on and upward, and in more senses than one, all flesh is grass."* Quote from an address of John James Ingalls, Senator of Kansas from 1873 to 1891. Cited by Barnes et al. (2003).

The assertion of Tilman et al. (2006) and Hill (2007) that biofuel derived from low-input high-diversity grassland does not displace food production is not compelling. Indeed, grasslands and forages play an important role in agriculture because they contribute to human food supply through animal production. Herbivores, notably domesticated species, have the unique ability to convert low-quality plant proteins into first-class meat and milk products (Fig. 1).

Humans in their adult state are unable to synthesize 8 of the 20 different amino acids required for the synthesis of the body proteins, either at all, or at sufficient levels to fulfil growth and maintenance (Follett and Follett, 2001). These amino acids, referred to as essential amino acids, must be necessarily obtained from food sources and include: leucine, lysine, isoleucine, methionine, phenylalanine, threonine, tryptofan and valine. In addition, during infancy histidine is also required (Follett and Follett, 2001). Animal proteins contain adequate amounts of all essential amino acids and are easily digestible. In contrast, plant proteins are deficient in at least one essential amino acid, usually lysine for cereals, methionine and cysteine for legumes, and are also less easy to digest (Smil, 2002). Yet, an additional aspect should be considered: ruminants combine the ability to digest cellulose-rich plant biomass with the ability to convert low-quality plant proteins into high-quality animal proteins. This allows the use of large areas of marginal land, unsuitable for cultivation of arable crops, for meat and dairy production (Loomis and Connor, 1992; Mannion, 1997).

**Figure 1.** Prairie biomass is edible by domesticated herbivores, and thereby is converted into high-quality milk and meat foods. Grazing herds directly utilize the forage, displacing fossil fuel for hay harvesting and transportation (photo Enrico Ceotto).

From the standpoint of energetics, meat and dairy products are not a good bargain: when grassland primary production is converted into animal products, most of the solar energy captured by the plants is lost as entropy (Mannion, 1997; Stiling, 1999); from 19 to 188 MJ of feed energy are required to produce 1 MJ of animal protein energy (Pimentel, 1992). Therefore, the energy efficiency of the conversion is very low. In particular, beef production is an inherently less energy-efficient way to produce proteins through animal feeding than milk production, because the animals have high metabolic rates, combined with long gestation and lactation periods (Smil, 2002). Pimentel and Pimentel (2003) pointed out that the meat-based American diet requires much more land, fossil energy and water resources compared with a lacto-ovo-vegetarian diet. Thus, it is tempting to imagine that there would be much more energy available from agriculture if we were all vegetarian. In practice, this is irrelevant. In fact, a diet rich in meat and dairy products is perceived as a symbol of prosperity, therefore vegetarianism will not likely be a voluntary choice for the majority of the population, either in rich or poor countries (Smil, 2002). Giampietro (2004) pointed out that the technical changes in the agriculture of developed countries have been driven by the demand for higher nutritional quality of the diet, rather than the need for increasing the energy supply of the diet. The opposite is true for typical diets of developing countries, where the pressure to harvest more dietary energy from cultivated areas in the form of cereals is overwhelming. Nevertheless, as soon as poor countries ameliorate their standard of life, there is an increasing demand for beef, beer and dairy products. This implies a higher cereal consumption per capita, thus increased fertile land requirement. Green et al. (2005) reported that:

- in developed countries, the meat production per capita is about 75 kg person$^{-1}$, data for the year 2000, albeit with a trend of slight decline from 1990 to 2000;

- in developing countries, in contrast, the meat production per capita is about 20 kg person$^{-1}$, data for the year 2000, with a trend of steady increase from 1980 to 2000.

This is in good agreement with Wilkins (2001), who highlighted different current pressures for developed and developing countries:

(i) In developed countries, concern about the adverse effects on health of consumption of saturated animal fats, coupled with little population growth, has decreased the demand for ruminant products; concern by society for environmental pollution has increased strongly, and new market opportunities have arisen from demand for "natural" production systems.
(ii) In developing countries, high rates of population growth, coupled with aspirations for a better diet, have increased the overall global requirement for food.

Smil (2002) pointed out that the actual protein intake is excessive in industrialized countries and is inadequate for hundreds of millions of people in poor countries. The economic development and changing lifestyles in developing countries, particularly in China, are causing a rising demand for meat and dairy products worldwide (Smith et al., 2007). As Lal (2007) recently pointed out, access to adequate and balanced food sources, along with safe drinkable water, is the most basic human right that must be respected. Therefore, there is considerable need for increasing animal production on marginal lands, and prairies might provide a substantial contribution. Rather than convert abandoned and degraded agricultural land into prairies for biofuels, conversion into productive pastures would provide much more significant benefits to humankind. Moreover, research has indicated that grass feeding reduces the ratio of omega-6 to omega-3 fatty acids in meat and milk; yet, conjugated linoleic acid (an anti-carcinogen) in milk is also much increased with grazing (Wilkins, 2001; Wilkins and Vidrih, 2000). Consequently, it is apparent that, even in terms of quality of products, grasslands have the potential to provide important services to society.

## 3. REACTIVE NITROGEN EMISSIONS

Nitrogen, along with carbon, is one of the most essential elements for life. However, many ecological problems arise when nitrogen is separated from its common partner carbon (Keeney and Hatfield, 2001). Nitrogen oxides, released during the combustion of fossil fuels and biomass, have a detrimental effect on global warming (Moomaw, 2002).

As highlighted earlier, one key strategy of the experiment planned by Tilman et al. (2006) was to exploit legumes as a main route of nitrogen in the ecosystems, with the purpose of avoiding the use of energy-intensive industrial nitrogen fertilizers. I do not disagree that this is an ecologically-sound strategy of nitrogen input, but I argue that the subsequent fate of fixed nitrogen must be taken into account. In fact, as Russelle et al. (2007) pointed out, one questionable point of the Cedar Creek experiment is that a substantial part of the energy gain for the conversion process of low-input high-diversity grasslands biofuel appears to come from combustion of biomass itself or by-products. In fact, regardless of whether biomass was co-fired with coal to generate electricity, converted into ethanol + electricity, or converted into synfuel + electricity, the critical point is that all nitrogen contained in harvested dry matter returned quickly to the atmosphere via combustion. This implies a dramatic reduction of the residence time of the biologically-fixed nitrogen. In contrast, in grazed grasslands, nitrogen, along with other plant nutrients, is recycled back into the soil via manure and urine (Barker and Collins, 2003; Jarvis, 2000; Wedin and Russelle, 2007). The residence time of nitrogen can be centuries in unmanaged grasslands and decades in grazed grassland (Galloway et al., 2003).

Leaves and stalks of grassland plants contain 10 to 20 N g kg$^{-1}$ dry matter, and rise to about 30 g N kg$^{-1}$ dry matter in the case of legumes. Such nitrogen contents are quite high if compared with cereal straw (5 g N kg$^{-1}$) and wood (3–5 g N kg$^{-1}$). When biomass is burned to generate energy, nitrogen oxides ($NO_x$), a mixture of nitric oxide (NO), and nitrogen dioxide, ($NO_2$), are released from two different pathways. The first is called thermal production and comes from the direct reaction of nitrogen and oxygen gas at high temperature ($N_2 + O_2 = 2NO$). The second is the oxidation of organic nitrogen compounds during pyrolysis at high temperature ($X\text{-}CH_2\,NH_2 + 3O_2 = CO_2 + 2H_2O + NO_2 + X$). Ozone, a substantial absorber of infrared radiation, is formed by $NO_2$ itself and $NO_2$ in the presence of volatile organic compounds. This leads to undesired feed-back: ozone is formed readily in a warm atmosphere, and is itself a greenhouse gas that promotes further warming (Moomaw, 2002).

Co-firing grasses with coal resulted in lower $CO_2$, sulfur dioxide ($SO_2$) and metals emissions, whilst nitrogen oxide ($NO_x$) emissions remained unchanged (Boylan et al., 2005). Therefore, it is advisable to generate renewable energy from biomass containing very low nitrogen per unit weight.

From the standpoint of reducing reactive nitrogen emissions, the use of maize grain ethanol appears to be a convenient solution. In fact, the by-product of the ethanol industry is distillers' dried grains with solubles, with about 30% crude protein and 11% crude fat (Belyea et al., 2004). Owing to their high nutritional value, distillers' dried grains with solubles are used mostly to feed dairy and beef cattle, but are also suitable to be added to pig and poultry feed (Shurson et al., 2004). This implies that all the nitrogen, along with fat, is recycled as an animal feed and only starch is used for bioenergy. Since part of the biomass is used to feed animals, the current claim that maize grain ethanol threatens food security and might lead to starvation in poor people in developing countries appears to be exaggerated. The same can be asserted for soybean (Glycine max, (L.) Merr.) biodiesel production: soybeans are crushed to separate oil from the meal, which is not combusted but rather used as a high-value protein source for feeding animals (Hill et al., 2006). Yet another point of strength for both maize grain ethanol and soybean biodiesel merits highlighting: the recycling of nitrogen, phosphorous and potassium within agricultural systems via manure has a substitution value for displacing the use of industrial fertilizers (Ceotto, 2005).

**Figure 2.** About one-half of dry matter produced by grain crops is in the form of inedible biomass. Owing to their low nitrogen content, crop residues are poorly suited for animal feeding, and well suited to be burned to obtain energy. Thus, crop residues have the potential to provide a strategic source of biofuels (photo Enrico Ceotto).

If ligno-cellulosic biomass has to be used for co-firing with coal, then straw and stover appear to be the most convenient feedstock. Since more than one-half of the dry matter produced by grain crops has no direct human nutritional value, crop residues have the potential to provide a strategic source of biofuels (Smil, 1999). Owing to their low nitrogen content, crop residues are poorly suited for animal feeding, except for maintenance of dry stock and as a fiber adjuvant for distillers' dried grains with solubles. On the other hand, they are well suited to be burned to obtain energy, associated with little reactive nitrogen emissions (Fig. 2). The use of cereal residues for energy generation certainly does not threaten global food security. On the contrary, an additional income derived from crop residues has the potential to stimulate farmers to produce more cereals. Nevertheless, a pitfall is just around the corner: crop residues play a crucial role in maintaining or increasing soil organic matter, a key condition for sustainable land use. Therefore, a crucial question arises: what is the fraction of crop residues that could be collected from the field without depleting soil organic matter and increasing soil erosion? Graham et al. (2007), referring to maize stover production in Iowa/Minnesota, concluded that about two-thirds could be collected without detrimental effects, while others have recommended lower amounts (Wilhem et al., 2004). If reduced tillage and crop rotations including forages are adopted, it is likely that a higher fraction of straw and stover could be used for bioenergy without detrimental effects. Still, the potential contribution from ley farming merits consideration: the alternation between grassland and arable cropping leads to accumulation of soil organic matter during the grass phase, which then breaks down during the arable phase, supplying nutrients that sustain crop yields (Wilkins, 2001). Moreover, integration of perennial pasture and grain crops leads to major environmental benefits in terms of insect and weed disruption, improved water-use efficiency and reduced soil erosion (Sulc and Tracy, 2007).

Finally, on marginal lands, grazing herds might directly utilize the forage, therefore displacing fossil fuel for hay harvesting and transportation. Admittedly, cattle herds are a source of $CH_4$, $NH_3$, $N_2O$ and $NO_x$ emissions, so they can negatively affect global climate change (Freibauer and Kaltschmitt, 2001; Asner et al., 2004). However, agricultural systems are inherently complex, and land-use choices entail rarely, if ever, "win-win" solutions. Some unintended trade-offs are inevitable, therefore "small loss-big gain" or "win-lose" solutions are good compromises for balancing human needs and ecosystem services (Defries et al., 2004).

## 4. BIODIVERSITY

Tilman et al. (2006) asserted that biofuel derived from low-input high-diversity grassland does not cause losses in biodiversity. Nevertheless, as Russelle et al. (2007) pointed out, they burned the plots, except for a narrow strip that was cut for biomass measurements. Thus, it seems likely their results do not properly represent a harvested system. Yet, their assertion is certainly true when prairies are compared with arable soils, but it is controversial if biofuel production is compared with pastures. In fact, two oak species, *Quercus macrocarpa* and *Quercus elipsoidalis,* were included in the list of 16 planted species, but the annual burning management did not allow survival of woody species in multi-species plots. On the contrary, grazing systems may lead to woody encroachment in the long term (Asner et al., 2004), with major advantages for both biodiversity and the C sink in above- and belowground biomass. Stuth and Maraschin (2000) suggested that grazing may reduce the competitive ability of grasses and allow woody plants to invade at faster rates; however, the reverse is also true: grazing may determine harsher environmental conditions at soil level, owing to less vegetation cover. Therefore, they postulate that the primary influence of grazing is the reduction of fuel loads, and therefore the occurrence of fire events, which may indirectly favor the diffusion of woody species.

On the other hand, high fertilizer applications and intensive grazing adversely affect biodiversity (Wilkins, 2001). Therefore, areas managed for high levels of biodiversity are likely to produce low yields of herbage with low feeding value (Tallowin and Jefferson, 1999). In principle, if the target of food and forage production is met by small areas managed for high agricultural yields, then vast areas could be managed for biodiversity. In practice, things are more complex: research is required to determine the best size and connectivity between land uses in order to achieve a successful biodiversity management (Wilkins, 2001; Green et al., 2005); pressure by society, deriving from tourism and recreational use of rural areas, should also be considered in land-use planning at higher integration levels (Wilkins, 2001). However, from the standpoint of tourism and recreational use, it seems likely that grazed grasslands are at least as attractive as prairies managed for bioenergy production.

## 5. EFFECTIVE LAND-USE RESOURCES

### 5.1. Historical overview

In prehistoric times people obtained food by collecting plant material and hunting animals. One hunter-gatherer individual had to collect about 33 MJ in the form of food every day to assure survival in his/her family unit (Loomis and Connor, 1992). At that time at least 1.5 $km^2$ of land (i.e. 150 hectares) were required to provide food for one person (Faidley, 1992). Grazing grasslands were vital to prehistoric people a long time before herbivores were domesticated (Barnes and Nelson, 2003). On a geological scale, agriculture is a recent development and dates back only 10 000–12 000 years. Shifting cultivation was one of the first agricultural practices, in which portions of land are cleared and burned to allow periodical cultivation of cereals. Shifting cultivation of forest lands supports a population of about 7.7 people $km^2$, about 13 ha per person (McCloud, 1998). The transition of shifting cultivation to subsistence farming did not increase productivity per hectare. In the Middle Ages, cereal yields in central Europe remained at about 1000 kg $ha^{-1}$ (Loomis and Connor, 1992). About 200 kg $ha^{-1}$ was required for seeding the subsequent year; about 400 kg $ha^{-1}$was required for feeding animals and to produce beer; the remaining 400 kg $ha^{-1}$was little more than the dietary need of the farmer who did the work (McCloud, 1998).

Cereal yields were doubled to 2000 kg $ha^{-1}$ from the 1600s to the mid-1700s. This revolution was introduced by livestock farming, in which cereals were rotated with clover and grasses for feeding animals, and manure and urine was returned to cropland (McCloud, 1998). The development of industrialized agriculture began in the early 1950s, when the use of industrial nitrogen fertilizers allowed spectacular yield increases. The Haber-Bosch process was initially used for producing explosives, but after the second World War, the production of industrial fertilizers had the consequence that humanity no longer had to rely on biological nitrogen fixation and limited natural resources of nitrogen fertilizers (Trewavas, 2002). Global cereal production has doubled in the past 40 years, and in addition to undeniable benefits, industrial agriculture has added substantial and environmentally detrimental amounts of reactive nitrogen, and phosphorus, to terrestrial and aquatic ecosystems (Tilman et al., 2002).

Penning de Vries (2001) indicated that with current yield levels, from 0.05 to 0.5 ha of land is necessary to produce the food an average human being consumes. This wide range depends on whether a strictly vegetarian or meat-based diet is considered. Yet, if all energy for human use (transportation, heating and cooking) were generated by energy crops, every individual would need from 0.2 to 2.0 ha of land. In the meantime, availability of land is becoming increasingly scarce due to land degradation, expanding urban and residential areas, and pressure from other human activities.

### 5.2. Wildlife-friendly versus land-sparing farming

As far as agriculture management is concerned, there are contrasting schools of thought on how to couple the solution of environmental problems with the fulfilment of dietary needs of an increasing world population. As Green et al. (2005) and Balmford et al. (2005) pointed out, two different sorts of land-use suggestions predominate in the literature: wildlife-friendly farming, whereby agricultural practices are made as benign as possible to the environment, at the cost of productivity per unit area, with increased pressure to convert marginal land to agriculture; and land-sparing farming, in which productivity per unit area is increased to potential levels and pressure to convert land to agriculture is consequently decreased, at the cost of higher risk of environmental pollution from smaller areas and threat to wildlife species on farmland. A long-lasting debate exists about the role of legumes. Some authors (e.g., Crews and Peoples, 2004; Drinkwater et al., 1998) suggest that sustainable land use would be greatly improved by using legume crops as a main source of nitrogen inputs. In contrast, others claim that the pressures to utilize crop plants that can fix nitrogen must be balanced against the equally important objective of achieving optimal utilization of solar energy per unit area. In this view, Sinclair and Cassman (1999) contend that the increasing food demand from the human population already exceeds the low carrying capacity of legume-dependent cropping systems. The industrial synthesis of ammonia provides the means of survival of about 40% of humanity; only one-half of today's population could be sustained by pre-fertilizer farming with a strict vegetarian diet (Smil, 2000). Pre-industrial agricultural systems rely solely on solar energy, but this implies low productivity per hectare, per hour of labor and per worker; thus, a dramatically lower standard of living (Fig. 3).

**Figure 3.** Plowing scene of the early 1930s. These pre-industrial agricultural systems rely solely on solar energy. Nevertheless, their low productivity per hectare, per hour of labor and per worker imply that: (i) more natural land has to be converted to arable crops to fulfil a production target; (ii) more people have to work in agriculture with a dramatically lower standard of living. (Painting by Franco Serafini, 1992).

In contrast, industrialized agricultural systems are relatively highly dependent on fossil energy, but they allow more land area to be devoted to non-agricultural purposes and assure a better quality of life for human populations (Fig. 4).

Achieving a more judicious use of fossil energy is a major challenge for science in agriculture, as well as in urban and industrial systems. However, low-input agriculture is not the obvious solution for the problem. In fact, if the productivity

**Figure 4.** Industrialized agricultural systems are relatively highly dependent on fossil energy, but they allow more land area to be devoted to non-agricultural purposes and assure a better quality of life for both agricultural and non-agricultural workers (photo Enrico Ceotto).

per unit area is lowered, larger areas of non-cultivated land must be converted into arable soil. De Wit (1979) pointed out that the most sensible use of fossil energy in agriculture is achieved when the highest yields per hectare are obtained from as small an acreage as possible by highly skilled farmers. Loomis (1983, p. 367) agreed, pointing out that the simplest strategy for efficient use of limited resources is generally intensive cropping: "*a system that comes rapidly to complete cover and extends the cover for the full growing season without limitation by nutrients, diseases and pests.*" This implies less energy use per unit of product, and more land available for other purposes. In this view, I would suggest that land-use decisions should be made on a higher spatial scale, involving a full weighting of benefits and trade-offs on fertile and marginal areas. An intriguing viewpoint was advocated by Giampietro et al. (1992): to assess the land area necessary to produce 1 kg of maize grain, we could consider: (i) only the area under maize cultivation; (ii) we could also include the area of fallow land required at farm level to allow sustainable production; (iii) we could also include the space requirement to produce the external inputs applied to the crops; (iv) finally, we could even consider the space of wild ecosystems needed to preserve the stability of the environment. As the scale of observation is enlarged, it is increasingly evident that the higher the productivity per land area, the larger the land space that can be exploited for other purposes. Trewavas (2001) estimated that without pesticides, irrigation or fertilizers, current food production would only be achieved by plowing up an extra 2000 Mha, with cutting down of forests and dramatic destruction of wilderness.

### 5.3. Low-input high-diversity prairies versus intensive land use

Tilman et al. (2006) emphasized that annual biomass production of native prairies increased with species diversity, with plots sowed to 16 species yielding 238% more aboveground biomass than plots sowed to a single species. The appealing inference that such mixtures of species provide a solution for effective land use is not justified (Grace et al., 2007). Indeed, the low-input high-diversity grassland average biomass production was 3700 kg $ha^{-1}$ $yr^{-1}$, equivalent to a gross energy output of 68.1 GJ $ha^{-1}$ $yr^{-1}$. With intensive management, an annual pasture production in temperate regions commonly reaches 15000 kg $ha^{-1}$ $yr^{-1}$, corresponding to 255 GJ $ha^{-1}$ $yr^{-1}$(Loomis and Connor, 1992). Therefore, 1 ha of intensively managed grassland can provide the same production as 3.74 ha of low-input high-diversity grassland. A well-fertilized and irrigated maize crop commonly produces about 22 000 kg $ha^{-1}$ $yr^{-1}$of aboveground biomass, one-half of which is grain and the other half is stover. The energy content of maize stover is about the same as grassland hay (i.e., 18 MJ $kg^{-1}$). Thus, 1 ha of maize grown for grain produces, as a by-product, an amount of biomass and energy about threefold that provided by low-input high-diversity prairies. Therefore, it is quite evident that the well-balanced mixtures of 16 plant species, including grasses, legumes and other forbs, cannot overtake the biophysical constraints imposed by nutrients, mostly nitrogen and phosphorous, and water limitations.

In order to assess the effectiveness of fossil energy use in agriculture, it is worthwhile to highlight some relationships between fossil carbon released and carbon assimilated by the crops.

Schlesinger (1999) indicated a factor of 1.436 moles of $CO_2$-C released per mole of nitrogen when accounting for the full carbon cost of nitrogen fertilizer, including manufacture, transport and application. When 1 kg of nitrogen is supplied to a field crop, about one-half is incorporated in aboveground crop biomass. The other half is accumulated in the soil nitrogen pool, transferred to the atmosphere as $NH_3$, NO, $NO_2$ or $N_2$, or lost to aquatic ecosystems in the form of nitrate (Galloway, 2005). Since the average nitrogen content of cereal crops is about 1.1% of dry matter, the uptake of 0.5 kg of nitrogen allows production of 45.5 kg dry matter with a 44% carbon content, corresponding to 20 kg C (Fig. 5). Thus, the carbon released for the industrial production of 1 kg nitrogen is about 7% of the net assimilation of a cereal crop, i.e., $1.436/20 = 0.07$. The carbon assimilation of a crop growing under non-limiting production conditions amply makes up for the fossil fuel-derived $CO_2$ emissions necessary to sustain its growth (Ceotto, 2005).

In the literature, there are many articles reporting thorough energy balances of land-use systems (Hill, 2007; Loomis and Connors, 1992; Pimentel, 2003; Tilman et al., 2006). Nevertheless, they normally contain evaluations and comparisons among 3 or 4 specific case studies, and extrapolation to other agricultural systems are hardly, if ever, possible.

## 6. CONCLUSION

There are two major disadvantages in deriving bioenergy from grasslands: (i) marginal lands are displaced from their fundamental role of producing meat and milk foods, thereby conflicting with the rising worldwide demand for high-quality

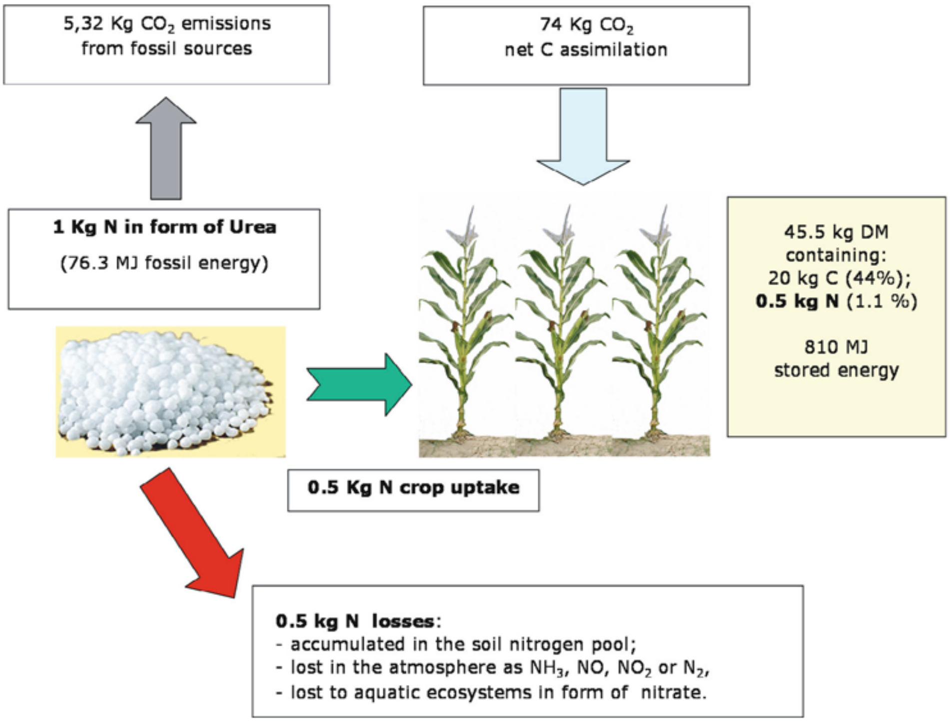

**Figure 5.** Outline of the major benefits and detrimental effects of supplementing industrial nitrogen on field crops. The amount of $CO_2$ assimilated by the crop plant amply makes up the $CO_2$ emissions deriving from the manufacture of industrial fertilizers. One-half of the nitrogen applied is taken up by the crop and provides valuable proteins to the food chain; the remaining half of the nitrogen supplied is undesirably lost in the environment.

food; (ii) combustion of N-rich grassland biomass or by-products releases reactive N into the atmosphere and dramatically reduces the residence time of biologically-fixed nitrogen. Since intensively managed crops on fertile soils need to be cultivated anyway to fulfil the dietary needs of populations, the potential role of inedible cereal crop residues in providing bioenergy should be considered. This might spare more marginal land area for forage production or even for full natural use, in order to sustain high levels of biodiversity. Performing a thorough energetic comparison among a few land-use systems is a relatively easy task. In contrast, to identify optimum land-use combinations at higher integration levels is not that simple. Owing to the complexity of terrestrial systems, and the complexity of interactions, a GIS-based modeling effort is needed in order to predict and quantify specific combinations of land use at higher integration levels. This could provide policymakers with the data needed to achieve broad societal goals.

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