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Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs

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Abstract

During the 20th century, farmers around the world replaced legume rotations and other traditional sources of nitrogen (N) fertility with synthetic N fertilizers. A sizable percentage of the human population now depends on synthetic N fertilizers for survival. In recent decades, N fertilizers have been linked to numerous environmental hazards including marine eutrophication, global warming, groundwater contamination, and stratospheric ozone destruction. Some researchers suggest that legumes, which can support biological N_2 fixation, offer a more environmentally sound and sustainable source of N to cropping systems. This perspective is countered by researchers who argue that, (1) legume-derived N has equally negative environmental impacts as the N derived from synthetic fertilizers, and (2) the human population now exceeds the carrying capacity of agricultural systems that depend on legumes for N inputs. In this review, we compare the sustainability of obtaining N from legume versus industrial sources in terms of ecological integrity, energetics and food security. We conclude that obtaining N from legumes is potentially more sustainable than from industrial sources. We further suggest that while some countries are fundamentally dependent on synthetic N for food production, many countries have the capacity to greatly reduce or eliminate dependence on synthetic N through adoption of less meat-intensive diets, and reduction of food waste.

Keywords: Legume; Fertilizer; Nitrogen; Energy; Security

1. Introduction

The shift from biological to industrial sources of nitrogen (N) that occurred on farms around the world during the 20th century constituted one of the most remarkable and profound transformations in agriculture. Smil (2001) has underscored the importance of this transformation by identifying the industrial process used to synthesize N fertilizers—the Haber–Bosch process—as the most important invention of the 20th century. Smil (2001) justifies this contention by explaining how 40% of all people alive today, and virtually all of those that will be added to the human population in the future, depend on the Haber–Bosch process as a major source of N for the synthesis of the proteins, DNA, and other N-containing molecules in their bodies. Put another way, much of the N in the tissues of 2.4 of the 3.5 billion people that were added to the human population since 1950 was derived originally from the Haber–Bosch process. By 2050, following Smil's logic and United Nations population projections (UN, 2000), as many as 5.5 billion people may owe their existence to synthetic N fertilizers; just a half billion shy of the current human population.

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The widespread adoption of N fertilizers has boosted the amount of food that farms can produce, and thus the number of people that can be fed, in two ways. First, when applied in adequate amounts, farmers can more effectively meet crop demands for N throughout the growing season and substantially increase yields (Silvester-Bradley, 1993). Between 1961 and 1996 aggregate world cereal grain production increased at a rate of 4.1% per year (Mosier et al., 2001). Some 40% of this increase has been attributed to increased productivity made possible by N fertilizers (Brown, 1999).

The second way that the adoption of N fertilizers increased overall farm yield was by allowing farmers to eliminate the fertility-generating stage of a rotation sequence. For example, before the advent of N fertilizers, it was typical to maintain 25–50% of a farm in a legume-rich pasture or cover crop which produced relatively few commodities, but regenerated soil fertility through biological fixation of atmospheric dinitrogen (N_2) by legume–rhizobial symbioses, and the buildup of slowly weathered nutrients in plant biomass (Crews, 1993; Smil, 2001). Through plowing and decomposition, the nutrients accumulated over one or more years of legume fallow or pasture were gradually released to subsequent crops. Although the harvested seed of some pulse (edible legume) crops contains much of the N_2 fixed by the legume plants during a growing season, the residues of legume pulse crops can under certain circumstances still constitute a net N input that becomes available to subsequent crops (Evans et al., 2001; Peoples et al., 2001). Legume-based rotations are still commonplace in sparsely populated countries such as Australia (Evans et al., 2001; Peoples and Baldock, 2001) where 91.7 million ha of pasture and forage legumes fix an estimated 4656×10^3 t N per year, and 2 million ha of crop legumes fix $\sim 310 \times 10^3$ t N per year (Unkovich, 2001). Legumes also remain important components of farming systems in resource-poor nations or where pulses form a part of the staple diet. In a country such as Nepal for example, 0.3 million ha of crop legumes are estimated to fix a total of 30×10^3 t N per year (Maskey et al., 2001).

However, legume rotations have progressively become less common as farmers in most countries of the world have increased their reliance upon synthetic N fertilizers. Accounts of N inputs in farming systems estimate that while as much as 50% of all available N may have originated from biological N_2 fixation by leguminous food, forage and green manure crops in the 1950s, this value had dropped to around 20% by the mid-1990s (Smil, 2001, 2002). The rapid adoption of synthetic N is reflected in global fertilizer consumption which increased from 10.8 Mt N per year in 1960 to 85.6 Mt per year in 2000 (FAO, 2002; Fig. 1). The introduction of N fertilizers presented an alternative to legume rotations that were expensive in both labor and land. Thus, in addition to increasing farmland productivity, the adoption of synthetic N fertilizers increased the overall farm production of food crops by allowing farmers to grow cereals or other crops on land that would have otherwise been dedicated to fertility-generating legume rotations.

Over the last decade there has been a bifurcation of perspectives on the use of synthetic N fertilizers in sustainable agricultural systems. On one hand, there is increasing public demand for food that is produced under various organic certifications, none of which allow for applications of synthetic N fertilizers. The area farmed using organic methods in the European Union has increased from 0.1 to 2.8 Mha between 1985 and 1998, with retail sales reaching US$ 5–7 billion in 1998 (Stockdale et al., 2000). In the US, retail sales of organic commodities exceeded US$4 billion in 1999 with markets expanding at a rate of 20–25% annually (Greene et al., 2001).

In contrast to the organic perspective, there are a growing number of ecologists and agronomists that contend that the food demands of our unprecedented human population exceed the potential productivity of legume-based agriculture (Sinclair and Cassman, 1999; Smil, 2001; Cassman et al., 2002). While low input agriculture is considered valuable for marginal lands (Sanchez, 2002), it has been argued that the productivity of the best farmlands should be maximized with efficient uses of inputs (Vitousek, 1994; Smil, 2001). The most important work for agroecologists in this case is not to transition away from dependence on synthetic N, but rather to increase the uptake efficiency of all N inputs and especially fertilizer applications (Cassman et al., 1998; Matson et al., 1998).

In this paper, we will outline what we believe to be the most important considerations for clarifying and resolving differences between these two perspectives. Coming to terms with these differences is not simply an academic exercise. Indeed, those interested in the

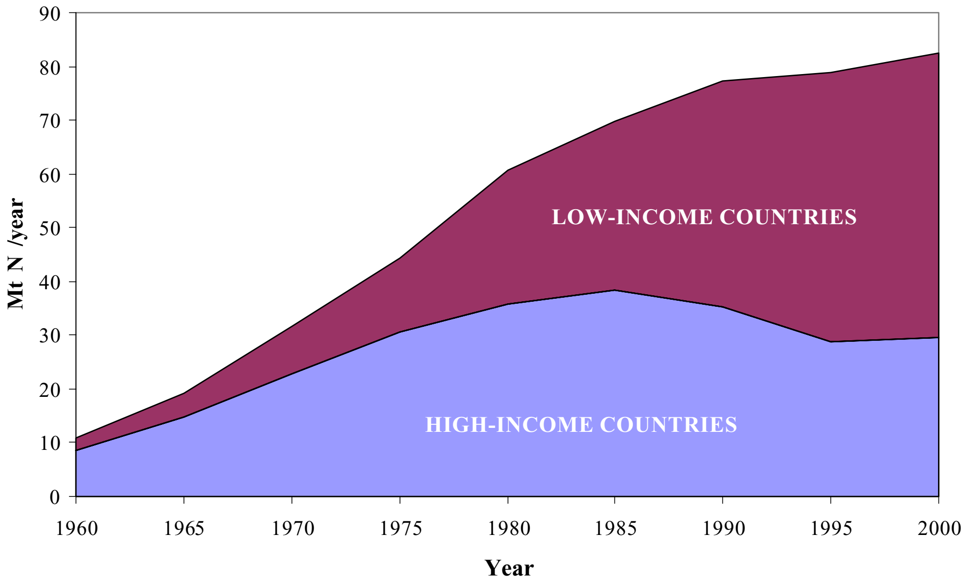


Fig. 1. Consumption of N fertilizers by low and high-income countries between 1960 and 2000 (Smil, 2001; FAO, 2002).

organic farming movement would like to know if they are simply wasting their time or even being counter-productive in the long-term by striving to eliminate use of synthetic chemicals on more of the world's farmlands. On the other hand, in deciding research priorities for making agriculture more sustainable while meeting human demands, should the scientific community focus its attention primarily on making N fertilizer applications more efficient? Or is it still valuable to work on developing and improving legume-based cropping systems at least in some regions?

In order to frame the discussion about how the choice to use industrial versus legume sources of N affects agricultural sustainability, it is essential to address two questions: (1) are there differences in environmental and social costs associated with using synthetic versus legume sources of N? and (2) is all of humanity equally dependent on the use of synthetic N to maintain a food supply?

2. Costs associated with legume versus synthetic nitrogen

Vitousek et al. (1997) reported how anthropogenic sources of N fixation have approximately doubled the global rate of N fixation of pre-industrial terrestrial ecosystems. Of the 140 Tg N estimated to be fixed each year by anthropogenic sources, between 25 and 40 originate from intensive legume cultivation, 80 from applications of synthetic N fertilizers, and 20 from fossil fuel combustion (Vitousek et al., 1997; Smil, 2002). There are numerous ecological consequences associated with humans doubling the amount of N cycling in terrestrial ecosystems. Synthetic N fertilizers are frequently identified as the main culprit of these ecological impacts (Vitousek et al., 1997; Fillery, 1999; Howarth et al., 2002), but this is primarily because N fertilizers comprise the greatest and most recent anthropogenic influence on the global N cycle. The question remains, is there a difference in the ecological sustainability of using legumes versus fertilizers to supply N to cropping systems? To address this question, we will compare these N sources from three perspectives: (1) ecological integrity, (2) energetics, and (3) food security.

2.1. Ecological integrity

Regardless of the N source, annual cereal-based farming systems generally have low efficiencies of N uptake by crops. It is typical for crops to take up 50%

or less of the N applied as N fertilizers (Peoples et al., 1995ab; Cassman et al., 2002), and some legume rotations have shown similarly low efficiencies of N uptake (Giller and Cadisch, 1995; Peoples et al., 1995b; Fillery, 2001). Some of these inefficiencies can be attributed to the volatile and mobile nature of N as well as the timing of nutrient supply and demand in annual cropping systems. Nitrogen leaves ecosystems through leaching of inorganic nitrate or dissolved forms of organic N, or through gaseous emissions to the atmosphere in the forms of ammonia, nitric oxides, nitrous oxide, or N_2 (Peoples et al., 1995a). All of these avenues of loss, with the important exception of N_2, are tied to one or more local, regional or global environmental hazards (Fig. 2; Peoples et al., 1995a). We will compare the most important environmental hazards associated with N losses in legume- and fertilizer-based systems, starting with the most local impacts and ending with the most global.

2.1.1. Soil acidification

The acidification of soils can reduce crop performance through various avenues including aluminum and manganese toxicities and reduced availabilities of numerous essential nutrients (Ritchie, 1989). The addition of reduced, inorganic N to soils in certain fertilizers (urea or anhydrous ammonia) or following ammonification of organic matter (such as legume residues) does not directly lead to soil acidification. For these inputs to contribute to soil acidification, ammonium must undergo nitrification to form nitrate, and then nitrate must subsequently be leached down the soil profile (Kennedy, 1992). In contrast, the application of ammonium-based fertilizers (ammonium

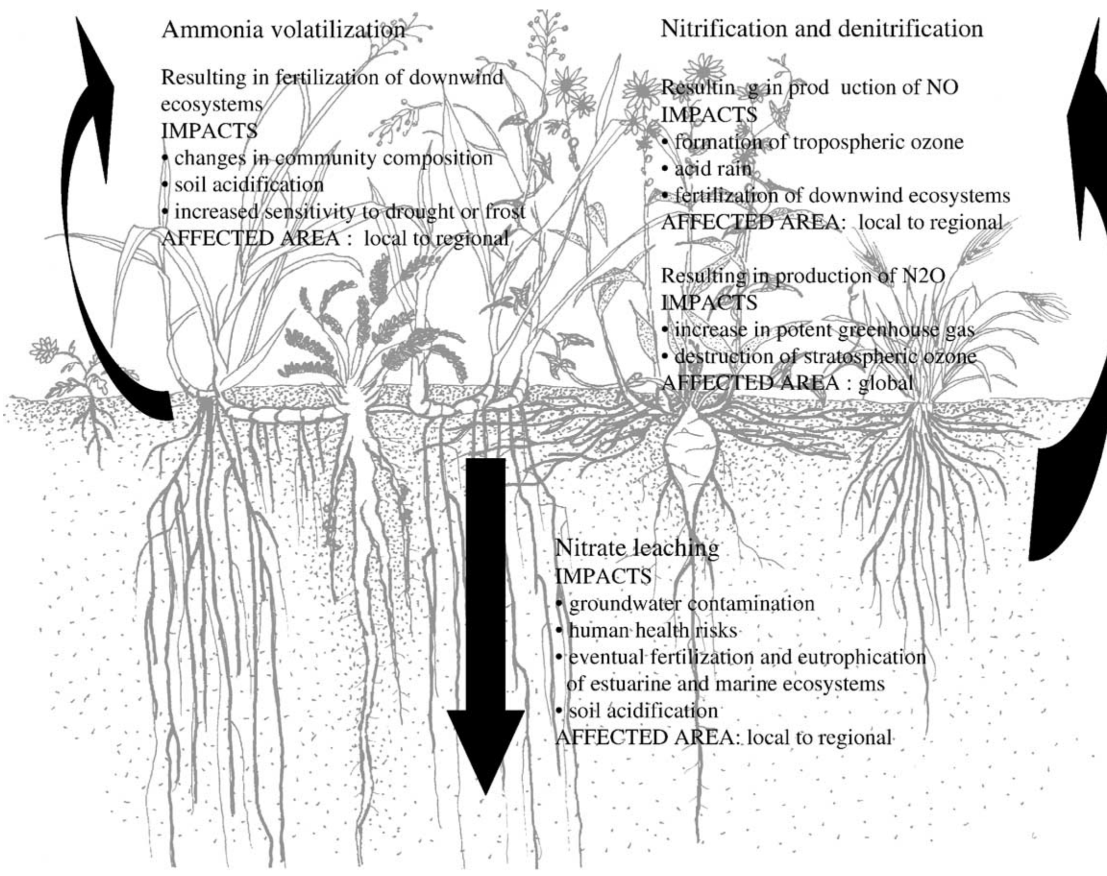


Fig. 2. Major avenues of N loss from agroecosystems and associated environmental hazards.

nitrate, ammonium phosphate or ammonium sulfate), increases the net H^+ concentration of soils, and thus directly contributes to soil acidification even in the absence of nitrate leaching (Kennedy, 1992).

Many legumes take up high concentrations of base cations, and in the process of balancing internal charge, release H^+ into the rhizosphere. This can result in soil acidification when legume biomass is harvested and removed from a farm. On the other hand, when legume biomass is incorporated back into the soil, no net soil acidification occurs.

2.1.2. Leaching of nitrate

Under conditions where nitrate has accumulated in the soil either from mineralization of organic matter or fertilizer applications, and water supplied via precipitation or irrigation exceeds crop demands, nitrate anions readily combine with base cations and leach through the soil profile. In regions with subsurface aquifers, the leaching of nitrate below the rooting zone commonly results in groundwater contamination. In a review paper, Spalding and Exner (1993) reported that ∼20% of the wells in the Midwestern US states of Iowa, Nebraska and Kansas exceeded the maximum contaminant level of 10 ppm nitrate established by the US Environmental Protection Agency. In the case of the widespread nitrate contamination of groundwater in Europe, excessive N fertilization has been implicated as an important contributing factor (Juergens-Gschwind, 1989). The most established health threat associated with nitrates in drinking water is the occurrence of the potentially fatal disease of methemoglobinemia that almost exclusively affects infants under 6 months of age (Smil, 2001). Although causation has been difficult to prove conclusively, evidence is mounting that nitrates in drinking water may also be linked to the development of certain cancers such as bladder cancer in older women (Weyer et al., 2001).

Leached nitrates can also flow laterally over impermeable soil horizons, or via groundwater basins into freshwater lakes or rivers. In most temperate regions, phosphorus rather than N is the nutrient most limiting to algae growth, thus N contamination of freshwater bodies does not necessarily result in a significant eutrophication hazard (Schindler, 1978). Although N does not limit primary production in temperate freshwater ecosystems, it does limit productivity in many estuaries and coastal marine ecosystems (Howarth et al., 2002). A dramatic example of this is the recent periodic development of a large hypoxia zone located near the Mississippi River delta in the Gulf of Mexico. Between 1970 and 2000, the amount of N that was leached from agricultural lands into the Mississippi and Atchafalya river basins approximately tripled (Goolsby and Battaglin, 2001). As a result, a eutrophic zone roughly the size of the state of New Jersey forms periodically causing oxygen depletion and ultimately hypoxia (Rabalais et al., 2002).

Nitrate leaching has been found to occur in both fertilized and legume-based cropping systems and grazed pastures across a range of environments (Dinnes et al., 2002; Fillery, 2001; Poss and Saragoni, 1992; White, 1988). It is especially high in soils with high hydraulic conductivities or artificially drained soils exposed to flood irrigation or high levels of precipitation. The greatest risk of N losses from legume-based systems occurs during summer or winter fallows after residue incorporation, but prior to establishment of the subsequent crop (Fillery, 2001). However, when leguminous cover-crops are allowed to grow throughout the fallow season, they serve not only to fix N, but also to scavenge soil available N. Used in this way, green manures have been shown to substantially reduce the risk of nitrate leaching experienced in various cropping systems (George et al., 1994).

There are relatively few studies that have directly compared nitrate leaching in legume and fertilizer-based systems. Limited evidence suggests that in some cases, nitrate leaching may be reduced when N is supplied by legumes compared to N fertilizers. For example, Drinkwater et al. (1998) measured leached nitrate from legume-based, manure-based and conventionally fertilized maize (*Zea mays*) cropping systems using lysimeters. The legume and manure-based systems averaged losses of 13 kg NO_3-N ha^{-1} per year while the fertilizer-based system averaged 20 kg ha^{-1} per year. In a different experiment where N-fertility of several perennial pastures was supplied by N fertilizer for 5 years and then by alfalfa (also known as lucerne, *Medicago sativa*) that was inter-seeded into the grasses, Owens et al. (1994) found that nitrate leaching was reduced by between 48 and 76% when the N source changed from ammonium nitrate to alfalfa. A number of other studies in grazed pastures have also indicated reduced leaching losses under grass-clover swards compared to fertilized grass (White, 1988; Whitehead, 1995). However, one should be cautious not to draw too many conclusions from such data since it is unlikely that many of these investigations used 'best-management' N fertilizer practices (Sinclair and Cassman, 1999). Furthermore, the outcomes from such comparisons will undoubtedly depend upon the rates of fertilizer N applied and, in the case of grazing systems, also be influenced by the legume content of the pasture (Cuttle et al., 1992) and whether the legume or grass species involved are annuals or perennials (Dear et al., 2001).

2.1.3. Ammonia volatilization

Ammonia volatilization of legume or fertilizer N can be substantial, especially in regions that are irrigated and/or have alkaline soils. In Europe, about half of the ammonia that is volatilized is deposited within a 50 km radius, while the other half is deposited over a much broader region (Ferm, 1998). Ammonia deposition can contribute to a whole host of ecological impacts in downwind ecosystems. For example, it can cause increased rates of soil acidification (Ferm, 1998), changes in plant community composition favoring N loving species (Wedin and Tilman, 1996), greater N fertility resulting in increased fluxes of nitrogen oxide trace gases, and greater sensitivity by the vegetation to drought or frost (Fangmeier et al., 1994).

Losses of ammonia following fertilizer applications to upland and lowland cropping systems can range from ~0 to >50%, while losses from flooded rice can reach as high as 80% (see review by Peoples et al., 1995a). Fertilizer placement, the timing of application, soil temperature and fertilizer type all play important roles in determining loss rates (Peoples et al., 1995a).

Ammonia volatilization from legume residues may be high when they are left on the soil surface, but the losses do not appear to match those measured in some fertilized systems. Larsson et al. (1998) estimated that 17% of the N in an alfalfa mulch was lost as ammonia within 30 days of placement. Janzen and McGinn (1991) measured 15% volatilization losses from a lentil (*Lens culinaris*) green manure when left on the soil surface, and Venkatakrishnan (1980) measured ammonia losses of 23% from a sesbania (*Sesbania rostra*) green manure after 63 days.

Losses of N by ammonia volatilization from legume residues as well as fertilizers can be greatly reduced or eliminated by incorporating amendments into the topsoil (Hauck, 1983; Janzen and McGinn, 1991; Larsson et al., 1998). It is worth noting that incorporating legume residues may reduce N losses through ammonia volatilization at the expense of increasing potential denitrification losses of N (Peoples et al., 1995a).

While there are not sufficient data to state conclusively that legume-N is less susceptible to ammonia volatilization than fertilizer N, there do exist a couple of mechanisms that would help explain such a difference. Singh et al. (1992) postulated that the temporary immobilization of N and the production of acidic products during cover-crop decomposition might reduce NH_3 volatilization losses. Moreover, the addition of green manures to flooded rice systems may have the effect of increasing the $p\mathrm{CO_2}$ in the floodwater, and reducing the pH and thus ammonia loss (Singh et al., 1992; Peoples et al., 1995a). Data by Diekmann et al. (1993) are consistent with such a mechanism, where flooded rice fields experienced greater percent losses when receiving N from urea compared to N from green manures.

2.1.4. Fluxes of nitrogen oxides

Nitric (NO) and nitrous oxides (N_2O) are trace gases that commonly form during the microbial processes of nitrification and denitrification. Emissions of NO impact the environment at local and regional scales. It contributes to the formation of tropospheric smog and ozone as well as acid rain and N fertilization of downwind ecosystems (Vitousek et al., 1997). The effects of N_2O emissions occur at the global scale. Nitrous oxide is a potent greenhouse gas which, on a per molecule basis, has >200 times the global warming potential as CO_2 (Peoples et al., 1995a). It can also catalyze the destruction of stratospheric ozone (Crutzen and Ehhalt, 1977). The N_2O concentration in the atmosphere has increased by about 13% in the last 200 years (NRC, 2001). Multiple activities have contributed to the anthropogenic increase in N_2O (Vitousek et al., 1997); however, fertilized agriculture appears to constitute the single greatest source, accounting for 70% of the increase (Matson et al., 1998).

Few studies have carefully compared N_2O fluxes between legume-based and fertilizer-based farming systems, and virtually no direct comparisons have been made of NO fluxes (Davidson and Kingerlee, 1997). Comparisons of N_2O emissions suggest little difference between legume and fertilizer-based agricultures. Robertson et al. (2000) measured N_2O emissions in a range of fertilizer- and legume-based cropping systems in Michigan, USA. Their data suggested that in spite of lower average nitrate levels in legume-based soils, annual N_2O emissions were not significantly different in the fertilized-based or legume-based cropping systems. They found that peak N_2O fluxes occurred with the onset of spring in the fertilizer-based systems, whereas fields with decomposing legume residues maintained lower peak fluxes, but sustained emissions for a longer period of time into the growing season.

In a literature review of N_2O emissions from 87 different agricultural soils, Bouwman (1996) reported fluxes ranging between 0 and 30 kg N_2O-N ha^{-1} per year with unfertilized control plots ranging between 0 and 4 kg N ha^{-1} per year. Fields planted in legumes have been found to maintain N_2O fluxes as low as 0–0.07 kg N ha^{-1} per year (Conrad et al., 1983). Other estimates of total denitrification losses (i.e. $N_2O + N_2$) from grazed clover-based pastures have been <5 kg N ha^{-1} per year (White et al., 2001). Measures of N_2O emissions equivalent to 2–4 kg N ha^{-1} per year have been reported for alfalfa after being plowed in (Bremner et al., 1980), or 6 kg ha^{-1} when cut and left on the surface as mulch (Larsson et al., 1998). However, alfalfa has been found to produce high N_2O fluxes elsewhere (Robertson et al., 2000) which may be associated with below-ground N release and mineralization after cutting. For example, Wagner-Riddle and Thurtell (1998) measured substantial spikes in N_2O fluxes during spring thaw in fall-plowed alfalfa fields, whereas no spike in N_2O fluxes occurred in spring when the alfalfa plants were left undisturbed. These findings imply that it is not the N_2-fixing activities of legumes *per se* that induce high N_2O fluxes, but the mineralization and subsequent release of available N that occur after cuttings or plow-down. There is also evidence, that N_2O can be produced by *Rhizobium*, the bacteria that fix atmospheric N_2 in the root nodules of legumes (O'Hara and Daniel, 1985), but it is difficult to evaluate what significance this observation may have in the field.

2.1.5. Overall global warming potential

Robertson et al. (2000) compared the combined greenhouse gas output ($CO_2 + N_2O + CH_4$) associated with a range of fertilizer-based and legume-based cropping systems. They did this by weighting each gas based on its potency as a greenhouse gas, and then aggregating the gases produced in each cropping system into a global warming potential index (GWP). In their study, the conventionally tilled and fertilized agroecosystem had a net GWP of 114, the legume-based tilled cropping system 41 and the no-till fertilized agroecosystem 14. The much higher GWP of the conventionally tilled and fertilized system compared to the legume-based system was primarily attributed to the fossil energy required to produce N fertilizers as well as the use of lime. While equivalent amounts of CO_2 were produced in lime applications and the production of N fertilizers for the no-till treatment, the sequestration of carbon (C) in no-till soils more than cancelled out the fertilizer and lime CO_2, resulting in a very low GWP.

It is important to point out that the low global warming potential estimated by Robertson et al. (2000) in the no-till system is a temporary phenomenon; once an equilibrium in soil organic matter dynamics is approached, then the GWP will ultimately climb to a value close to that of the conventional, fertilizer-based agroecosystem. Thus in the long run, the legume-based system will likely have the lowest global warming potential of the cropping systems studied by Robertson et al. (2000).

2.1.6. Synchrony of nitrogen supply and demand

Many ecological variables interact to determine the incidence of the environmental hazards associated with N losses described above. However, one seems to stand out among the others—the extent to which nitrate is allowed to accumulate in soils under any cropping system (Cassman et al., 2002). If crop demands for N are closely synchronized with processes that regulate N availability in the soil, then little nitrate is allowed to accumulate, which in turn minimizes soil acidification, nitrates in groundwater and production of N trace gases.

Some have argued that legume-based agroecosystems maintain or have the potential to maintain higher levels of synchrony because rates of N mineralization following legume decomposition are more likely to synchronize with rates of N uptake by crops, when compared to single or dual applications of N fertilizers (Becker and Ladha, 1997; Gliessman, 1998).

However, the data are not conclusive. While there are some studies that show relatively greater N synchrony in legume-based systems (Janzen et al., 1990; Diekmann et al., 1993), others suggest that fertilizer-based systems are superior (Harris et al., 1994; Cassman et al., 1996). While fertilizer-based systems generally do experience greater nitrate accumulation following fertilizer applications during the growing season, both fertilizer and legume-based systems are vulnerable to nitrate accumulation during significant parts of the year when soils are not cropped (Campbell et al., 1994; Fillery, 2001). The potential advantage of N fertilized systems is that crops can receive multiple top-dressings during the growing season in an attempt to better match N supply with crop N demand (Cassman et al., 2002). Alternatively, several researchers have suggested that one of the most promising directions for increasing N synchrony is the further development of perennially-based cropping systems (Myers et al., 1997; Ewel, 1999; Dinnes et al., 2002; Cox et al., 2002).

2.1.7. Monocultures versus rotations

The ecological tradeoffs of legume and fertilizer-based farming systems discussed thus far have, for the most part, been directly tied to the N cycle. It is arguable that other agronomic challenges such as insect, weed and disease infestations have intensified over the last 50 years in part because of the ecological and evolutionary dynamics of monoculture production (Gliessman, 1998). Before the widespread adoption of synthetic N fertilizers, farmers generally maintained legume cover crop, grass-legume pasture or fallow rotations. These cropping cycles not only served to regenerate soil fertility, but also helped to maintain manageable pest populations and retard pest evolution. Certainly the use of synthetic fertilizers does not prevent a grower from employing a crop rotational sequence, but history shows that there is a powerful tendency to specialize in one or two most profitable crops for which farmers have equipment and markets.

A reliance on legumes for N encourages the inclusion of a cover crop or pasture rotation. Such rotations have been shown to reduce weed seed banks (Liebman and Dyck, 1993), reduce crop losses to some insect pests (Letourneau, 1997) and diseases (Matson et al., 1997) compared to monocropped farming systems. Indeed, Giller and Cadisch (1995) raise concerns about the potential development of genetically engineering grain crops that are capable of fixing atmospheric N_2 because such a discovery could facilitate the adoption of more widespread monocropping practices, and the ecological and evolutionary problems associated with them.

2.2. Energy and nitrogen

The *Rhizobium* or *Bradyrhizobium* bacteria that fix N from within root nodules of legumes obtain their energy as photosynthate from the host plants. Atkins (1984) reported that between 3 and 25% of a legume's net photosynthate may be allocated below-ground to support N_2 fixation. Some of this C may be used directly to maintain nodule function, while some is returned to the host plant in the form of C-skeletons of the exported nitrogenous solutes (Atkins, 1984). On the scale of the farming system where a legume rotation is included in part to supply N to subsequent crops, the photosynthate cost of fixing N_2 is internalized and highly renewable. Essentially solar energy is used to fix N by the plant/bacteria symbioses; however, accruing N in this way should not be considered to be 'free' in terms of its impact on plant growth.

Synthetic N fertilizers are the single most energy expensive input to modern agricultural production accounting for approximately 68% of on-farm commercial energy use in less developed countries and 40% in more developed nations (Mudahar and Hignett, 1987). The energetic costs of synthesizing N fertilizers remains very high even when the industrial fixation of ammonia has greatly improved in energetic efficiency over the past 50 years from >80 $GJ\,t^{-1}$ NH_3 before 1955 to 27 $GJ\,t^{-1}$ NH_3 in the most efficient plants operating in the late 1990s (Smil, 2001).

That N fertilizers comprise a relatively small fraction of society's total fossil fuel consumption has led some to suggest that energy availability will not limit our ability to make enough N fertilizers over the next century (Smil, 2001). Indeed, it appears fairly certain that aggregate global oil and gas resources are sufficient to meet expected demands for at least 50–100 years (Rogner, 2000). While we believe this perspective is reasonable in the short to medium term, in the long term (i.e. >25–100 + years) the energy related concerns stemming from our species' dependence on synthetic N are serious:

- Energy resources are not distributed equally, leaving many countries with uncertain energy futures. In 1997, 14 countries imported more than 75% of the energy they consumed and another 22 imported >50% of the energy they used (BP, 2001). While globally, only about 1.3% of all energy produced is used for fertilizers (Smil, 2001), the cost of fertilizers will climb as finite commercial energy resources are increasingly used for other purposes.
- In 2001, the Intergovernmental Panel on Climate Change predicted that human activities will result in a mean increase in global temperature by between 1.4 and 5.8 °C this century (Houghton et al., 2001). Corroborated by an expert panel appointed by the US National Academy of Sciences, this prediction and its wide ranging implications, almost guarantee that on a global basis, greenhouse gas regulations are likely to constrain fossil energy use more than the availability of fossil fuel supplies over the next century. The C cost of synthesizing N greatly increases the net global warming contribution of farming systems (Schlesinger, 2000).
- Even if fossil fuel supplies are sufficient to support the energy-rich lifestyles of developed nations and grow the economies of China, India and other developing nations through this century, what then? The human population in 2050 is projected to be ~9.1 billion (UN, 2000) and as much as 60% of the human population will owe its existence to synthetic N fertilizers. Given that ultimate reserves (known and predicted resources) of fossil fuels will be largely exhausted in the later half of the 21st century (Rogner, 2000), is it wise to put faith in the development of an unproven or unknown energy source to maintain our species beyond the next 100 years? If solar-hydrogen or some other renewable energy source is developed that can meet our needs, then this concern will no longer stand. However, until that time, we question the "life history strategy" of a species that has become existentially dependent on the abundant and inexpensive availability of a non-renewable energy source for the procurement of food.

2.3. Food security

There exist today countries that either due to reasons of poverty or politics do not have access to fertilizers. For example, Sanchez (2002) recently reported on the status of food production south of the Sahara in Africa. He emphasized the importance of research on legume-based cropping systems that are economically and technically accessible to farmers. According to Sanchez, the level of poverty in this region is such that use of fertilizers and other expensive inputs is prohibitive.

The experience of Cuba since the demise of the Soviet Union in 1991 provides a clear example of how political isolation can result in a crop fertility deficit. Before 1991, Cuba received large quantities of fossil fuels and fertilizers from the former Soviet Union (ERS/USDA, 1998). In 1988 Cuban farmers applied 598 thousand metric tons of fertilizer to croplands, whereas by 1994 this rate had dropped to 124 thousand metric tons (FAO, 2002). In order to survive after 1991, Cuban agriculture transformed from relying primarily on fertilizer-N to grow sugar cane, to legume-N to grow food staples. Regardless of where people stand in the ideological conflict that led to Cuba's economic isolation following the demise of the Soviet Union, the experience of Cuba illustrates how political conflicts can profoundly affect food security indirectly through availability of energy and nutrients.

3. Shifting from fertilizers to legumes

If increasing the role of legumes as a N source becomes a goal, will it even be possible given that already ~40% of humanity may owe its existence to the use of N fertilizers? We contend that the answer is yes—it could be achieved in particular places by either increasing the amounts of N_2 fixed where legumes are already included in cropping systems, reducing the amount of N lost from legume-based cropping systems and/or increasing the amount of land planted under legumes.

3.1. Increasing N_2 fixation and decreasing N losses in cropping systems that already involve legumes

Based on work by Giller and Cadisch (1995), Peoples et al. (2002) devised a simple model (Fig. 3) that illustrates the relative importance of different approaches to increasing N_2 fixation and a relative timeline for when the approaches might be ready

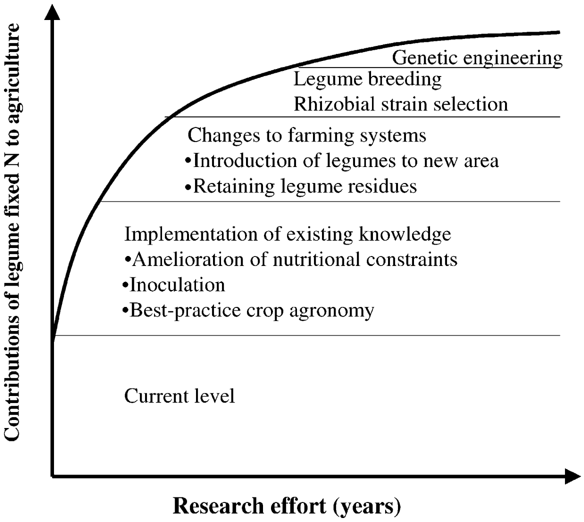


Fig. 3. Prospective technological changes in legume-based farming systems that have the potential to increase the contribution of fixed N to agriculture. Research effort: time required before technology could be available for use (Giller and Cadisch, 1995; Peoples et al., 2002).

for implementation. The model suggests that the approach to increasing the contribution of fixed N to agriculture that would have the greatest impact is in the local fine-tuning and implementation of agronomic knowledge that already exists (Giller and Cadisch, 1995; Peoples et al., 2002). Specifically, N_2 fixation by legumes could be increased, and in some places substantially, by fertilizing with deficient nutrients (especially phosphorus), making sure the crop legumes are inoculated with effective and efficient rhizobia, and addressing other agronomic limitations such as subsoil constraints to deeper root penetration, soil acidity, water stress, and high N carryover from previous crops (Giller and Cadisch, 1995). How to address these constraints is well understood. What is less clear is how to contend with resource, training and economic limitations in putting best management practices into action.

Peoples et al. (2002) contend that beyond better implementation of what we already know, the next approach to increasing N_2 fixation is research and implementation of alternative cropping systems that include different legumes, and emphasize nutrient conservation (Fig. 3). More distant in the future, and less likely to result in dramatic increases in N_2 fixation are further breeding and selection efforts for legumes and rhizobia, as well as modification of legumes and/or rhizobia through genetic engineering (Giller and Cadisch, 1995; Peoples et al., 2002).

As mentioned earlier in this review, N losses from agroecosystems are commonly the result of asynchrony between rates at which N is made available in the soil and patterns of crop N uptake. As with the range of approaches to increasing N_2 fixation in legumes, there are a range of approaches that could reduce N losses from legume-based cropping systems; some well known and ready to be implemented, and others that need substantial development before becoming viable (Fig. 4).

The most immediately viable strategy for increasing N synchrony in legume-based or fertilizer-based systems is to minimize the time that fields are left exposed without vegetation (Fig. 4). This can involve a range of approaches such as planting cover-crops in the off-season, oversowing pasture or cover-crops into a near-mature crop, or plowing in pasture or cover-crops in the spring rather than autumn (George et al., 1994; Robertson, 1997; Shipley et al., 1992). Including perennials in annual cropping systems will maintain the capacity to take up soil N when annual crops are being re-established. Examples of mixed annual/perennial systems include alley cropping

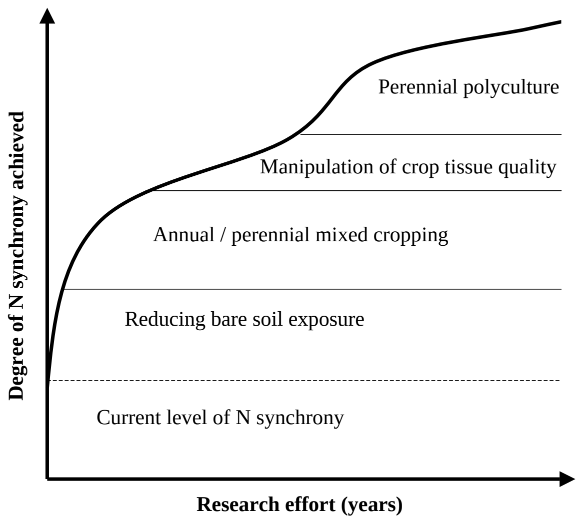


Fig. 4. Prospective advances in cropping systems research that have the potential to increase the synchrony of N inputs from legume fixation and N uptake by non-legume crops. Research effort: time required before technology could be available for use.

plantings that involve sowing grain crops in the space between rows of legume or actinorhizal trees or shrubs (Crews and Gliessman, 1991; Lefroy et al., 2001; Sanginga et al., 1995), and alfalfa/grain intercropping (Abdel Magid et al., 1991; Harris et al., 2003). The inputs of fixed N by the N-fixing perennials in such systems can be substantial (Ladha et al., 1993; Sanginga et al., 1995), and the lateral network of perennial roots that develops at depth beneath the cropped areas can recover much of the excess water and leached nitrate or nutrients escaping the crops or lost during the fallow period (Lefroy et al., 2001; Sanginga et al., 1995).

While annual/perennial mixed cropping systems are traditional in some regions, and reasonably well studied in others, there still is a need for further research to devise regionally specific farming systems that minimize potential problems of excessive competition for light, nutrients and/or water between the perennial and annual crop (Harris et al., 2003). In theory, N synchrony can also be optimized by manipulating C:N ratios of pasture, cover crop or intercrop residues through careful selection of crop varieties and mixtures (Myers et al., 1994). The effect of plant tissue quality on decomposition and N mineralization rates has been well documented (Myers et al., 1994; Peoples et al., 1995b; Fillery, 2001), but a great deal of work remains to test and optimize different crop combinations appropriate to particular regions.

The furthest off in time and potentially most far-reaching approach to increasing N synchrony is the development of mixed perennial cropping systems such as those being investigated by the Land Institute in Salina, Kansas, USA (Soule and Piper, 1992; Cox et al., 2002). A cropping system that includes multiple perennial species with different spatial and temporal nutrient uptake patterns has the potential to improve N synchrony well beyond annual-based systems (Robertson, 1997; Ewel, 1999; Dinnes et al., 2002).

3.2. *Freeing up land for legume cover crops or pastures*

Smil (2001) has estimated that 40% of humanity is fundamentally dependent on synthetic fertilizers. However, as Smil points out (2001), this dependence is not evenly spread around the world; some countries such as Indonesia are overwhelmingly dependent on fertilizer inputs, while others such as Austria, have little to no "existential" dependence. This may seem counterintuitive, given that in 1998, an average of 92 kg N ha^{-1} per year was applied to farmland in that country (FAO, 2002). Yet numerous countries that currently apply large amounts of synthetic N have the potential to reduce these applications by allocating land to legume rotations. Ways that countries could make available land for legume rotations without bringing new land into production include: (1) reducing food waste and storage losses; (2) reducing net food exports; (3) reducing meat consumption in countries that feed grain to livestock and maintain high levels of meat consumption.

If less grain and other foodstuffs were lost in harvesting or in post-harvest storage to insects or disease, or wasted by consumers, the amount of land that is currently dedicated to growing these crops could be cropped to legumes. Harvest and post-harvest losses of cereals commonly exceed 10% in most countries (Smil, 2000); however, reducing harvest and post-harvest losses (especially to pests) may present a formidable challenge to farmers in less developed countries and in the short term may not be possible. By contrast, reducing post-harvest losses of food, especially those which are simply wasted in more developed countries, could be curbed with almost no lifestyle impacts. According to research by Smil (2001), the US food system supplies 80% more food calories for its population than are actually consumed. But the US is not alone. Actual per capita caloric consumption in the US is around 2000 per day (Smil, 2001). If the caloric *supply* (as opposed to consumption) of the most food-wealthy countries was simply reduced to 3000 calories per capita per day, then substantial areas of land could be available for legume N_2 fixation (Table 1). These estimates are quite conservative on two accounts. First, our calculation is based on a partial reduction of food wastes; if wastes were reduced even further, more land would be available for legume-based cropping systems. Second, we assume that food wastes are cereals, which have high caloric values. In reality, fruits, vegetables and meats comprise a significant fraction of food wastes. Since these foods require more land to produce a given number of calories

Table 1
Area of land made available to legumes and percent of lands under grain production that could be sustained with legume-N following (1) a reduction in food supply to 3000 calories per person per day, or (2) elimination of net grain exports

Country	3000 calories per person per day		No net grain exports	
	Hectares available to legumes	Percentage of land in grain production	Hectares released to legumes	Percentage of land in grain production
Argentina	96687	1	6204854	61
Australia	227838	1	11288250	69
Austria	81514	11	78598	9
Belarus	131342	6		
Belgium	91857	36		
Bulgaria			299776	15
Canada	139251	1	7282939	40
Czech Republic	64311	4	177279	11
Denmark	37537	3	230451	15
Egypt	296520	13		
Finland	22341	2	48675	4
France	438300	5	4317458	46
Germany	527447	8	1250053	18
Greece	207946	19		
Hungary	309286	12	772819	27
India			895697	1
Ireland	34944	13		
Israel	119303	100		
Italy	605549	18		
Jordan	6243	8		
Kazakhstan	263454	2	7851245	69
Korea, Rep.	125095	12		
Kuwait	7992	100		
Lebanon	38247	100		
Libyan Arab Jam.	208645	100		
Lithuania	41885	4		
Mexico	375308	4		
Moldova Rep.			51539	6
Morocco	121370	100		
Myanmar	0	0	139054	2
Netherlands	241971	8		
New Zealand	25351	23		
Norway	39533	14		
Paraguay			52545	9
Poland	491752	6		
Portugal	223744	76		
Romania	232270	4		
Slovakia			102210	12
Slovenia	3698	4		
Spain	381227	6		
Suriname			3823	7
Sweden	41894	3	279084	22
Switzerland	25603	16		
Syrian Arab Republic	364914	12		
Thailand			2319411	20
Tunisia	209382	20		
Turkey	1533488	12		

Table 1 (*Continued*)

Country	3000 calories per person per day		No net grain exports	
	Hectares available to legumes	Percentage of land in grain production	Hectares released to legumes	Percentage of land in grain production
Ukraine				
United Arab Emirates	67236	100		
United Kingdom	259766	8	359854	11
United States	3596414	6	14184417	23
Viet Nam			232888	40
Yugoslavia	9581	0	120259	5

than cereals, a reduction in food wastes would result in a greater amount of land released than we list in Table 1.

Countries that currently grow enough food to sustain their populations and also export a significant amount of food could reduce dependence on synthetic fertilizers by taking land out of export crop production and planting it instead to N_2-fixing legumes. For example, in recent years, Australian farmers have steadily increased the synthetic N they apply to cropland, reduced the area of legume-based pastures, and replaced legume crops with canola (*Brassica napus*) as the main 'break crop' in rotations (Angus, 2001). At the same time grain exports (particularly wheat) have increased so that ∼69% is now exported (FAO, 2002). Even though Australia relies to a greater extent than almost any other developed country on legumes for N (Unkovich, 2001), it could eliminate any need for N fertilizers by shifting land out of export crops into legumes. We are not suggesting that substituting legumes for cereals is economically feasible or even philosophically desirable; nor are we suggesting that

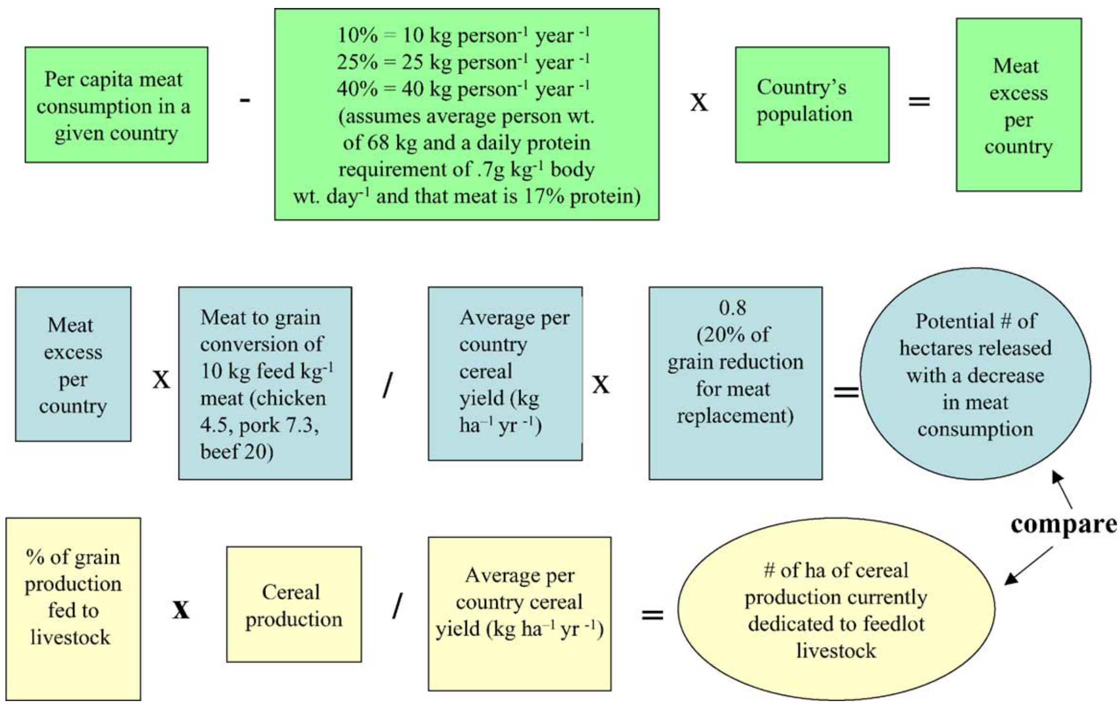
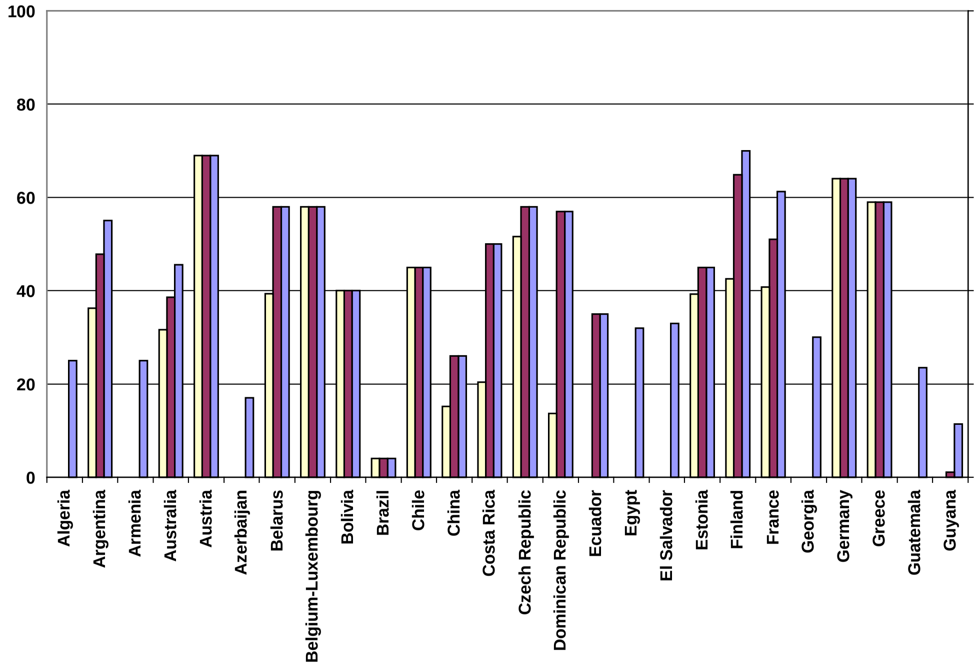
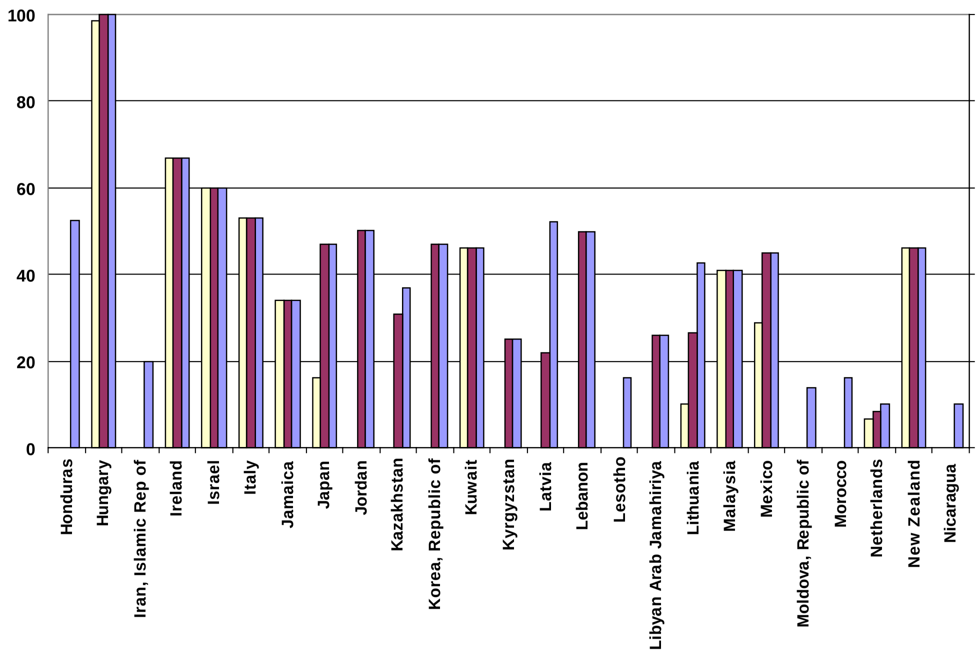


Fig. 5. Approach to estimating the potential for different countries to convert cereal lands to N-fixing legumes by reducing grain fed to livestock.

countries reduce grain exports to the point of starving people in other countries. However, research into how much exported grain is simply being used as livestock feed in high income or rapidly developing countries versus supporting low-income populations with food is worth undertaking.

The final way that many countries could make available land for legume rotations and reduce reliance





on N fertilizers would be to reduce the consumption of meat produced in feedlots. Because it requires on the order of 4.5, 7.3 and 20 kg of feed to produce 1 kg of chicken, pork or beef, respectively (Smil, 2001), diets high in feedlot-produced meat necessitate large areas of land dedicated to annual grain production. If less feedlot-meat were consumed, then land could be freed up from continuous grain production allowing for more land-expensive legume/grain rotations (Fig. 5). In Fig. 6, we estimate the percentage of cropland in different countries that are currently sown to cereals, but could be used to grow N_2-fixing legumes if diets change so that meat comprised 40, 25 or 10% of protein requirements. These estimates of the relationship between meat protein consumption and land available for legume rotations are very conservative. The calculations do not include the meat that could potentially be produced by grazing in newly established legume pasture rotations.

The amount of land planted to legumes that is required to sustain the N fertility of grains and other crops varies with legume species, climate and soil type (Crews, 1996; Peoples and Baldock, 2001; Peoples et al., 2001). However, if for the purposes of a broad stroke comparison, we assume a typical ratio of 1 unit area legume: 1 unit area crop, then virtually every country in Fig. 6 that could convert >50% of its croplands to legumes through a given level of meat-protein

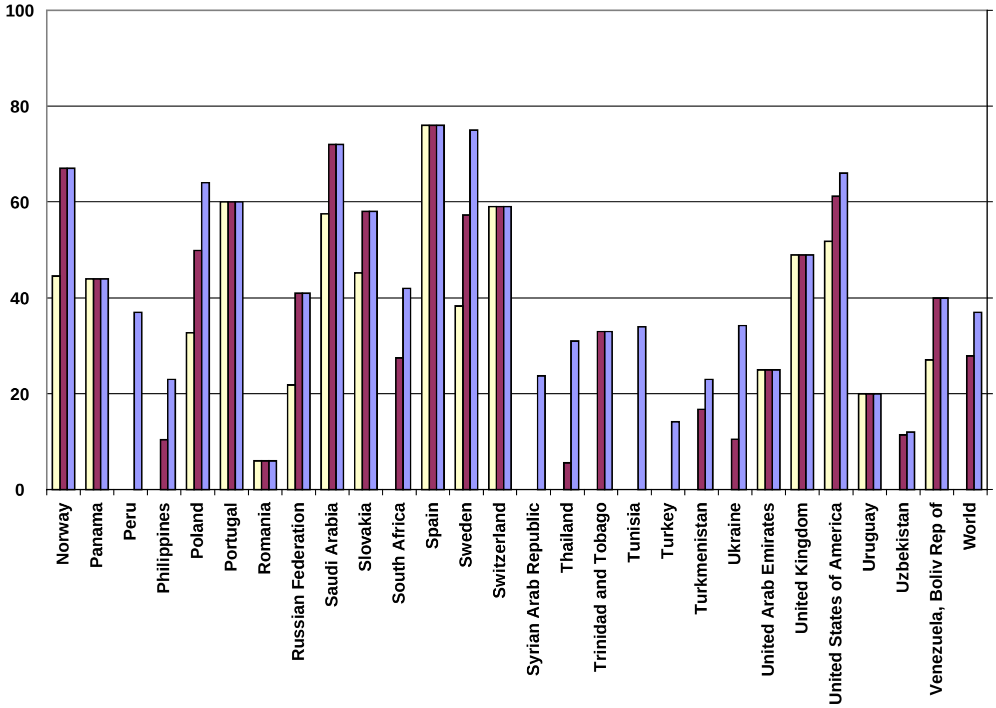


Fig. 6. Percentage of land area currently planted to grain crops that could be converted to legume N-fixing rotations if meat consumption were reduced to constitute 40 (white bars), 25 (black bars) or 10% (gray bars) of protein requirements. The analysis only applies to countries that feed grain to livestock. Countries, territories or provinces that were not included in the assessment due to unreported data in the FAOSTAT dataset were: American Samoa, Andorra, Aruba, Bahrain, Bhutan, British Indian Ocean Territory, British Virgin Islands, Cayman Islands, Christmas Island, Cocos Islands, Cook Islands, East Timor, Equatorial Guinea, Faeroe Islands, Falkland Island (Malvinas), Gaza Strip, Gibraltar, Greenland, Guadeloupe, Guam, Iceland, Kiribati, Liechtenstein, Marshall Islands, Martinique, Micronesia, Montserrat, Nauru, Niue, Norfolk Island, Northern Mariana Island, Oman, Palau, Puerto Rico, Qatar, Reunion, Saint Helena, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent/Grenadines, Samoa, San Marino, Singapore, Tokelau, Tonga, Turks and Caicos Island, Tuvalu, US Virgin Islands, Wallis and Futuna Island, West Bank, Western Sahara. If a country is not listed in the body of the figure or in the list of countries that were eliminated for incomplete data sets, then our analysis indicates that it has no potential to free up land for legumes by reducing the amount of grain fed to livestock. See Fig. 5 for assumptions and calculations. *Sources*: FAO (2002); WRI (2000).

reduction could eliminate its dependence on N fertilizers for grain production.

4. Conclusions

Based on limited data from comparisons of typical legume rotations and fertilizer management practices, our review suggests that the ecological integrity of legume-based agroecosystems is marginally greater than that of fertilizer-based systems. The difference between the two N sources is not nearly as marked as many advocates of sustainable/organic farming believe. Moreover, it remains to be seen whether fertilizer or legume-based annual cropping systems will maintain greater ecological integrity when best management practices are compared.

The energetic basis of N_2 fixation in legume versus fertilizer-based systems is arguably the greatest factor that differentiates the sustainability of the two N sources. Nitrogen biologically fixed by legumes is ultimately derived from solar energy, while fertilizer N requires significant amounts of non-renewable fossil fuels or other commercial energy sources to produce.

As the uses of known commercial energy resources are constrained in the next century due to global warming or resource exhaustion, many countries may not be able to count on an uninterrupted supply of energy or N imports due to poverty or political conflicts.

We agree with Smil (2001), Sinclair and Cassman (1999) and others who have argued that humanity has overshot the ability of legume-based agriculture to feed all of our population. However, we contend that the tremendous variation in attributes of individual countries—demographic, economic, consumptive, edaphic, climatic and energy resource—has led to a world where many countries are fundamentally dependent on N fertilizers for food, while others have moderate to virtually no existential dependence.

A wide range of countries could begin to reduce their use of N fertilizers through a change of diet, trade policies or through food waste reduction. We contend that steps toward greater agricultural sustainability—both in terms of ecological integrity and energetics—should be taken where possible.

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