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Energy intensities and greenhouse gas emission mitigation in global agriculture

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Abstract Energy efficiency and greenhouse gas emissions are closely linked. This paper reviews agricultural options to reduce energy intensities and their impacts, discusses important accounting issues related to system boundaries, land scarcity, and measurement units and compares agricultural energy intensities and improvement potentials on an international level. Agricultural development in recent decades, while increasing yields, has led to lower average energy efficiencies when comparing the 1960s and the mid 1980s. In the two decades thereafter, energy intensities in developed countries increased, but with little impact on greenhouse gas emissions. Efficiency differences across countries in the year 2000 suggest a maximum improvement potential of 500 million tons of CO_2 annually. If only below average countries would increase their energy efficiency to average levels of the year 2000, the resulting emission reductions would be below 200 million tons of CO_2 annually.

Keywords Energy intensity · Agriculture · Greenhouse gas emissions · Global mitigation potential · Fertilizer efficiency

Introduction

In its fourth assessment report (AR4), the authors of the agricultural chapter for IPCC working group III (Smith et al. 2007a) did not include emission mitigation potentials from increased energy efficiency, though they reported a figure derived in Smith et al. (2008), for comparison with other measures. Energy efficiency was not included in the agricultural mitigation chapter of IPCC AR4 in order to avoid double counting, since efficiency increases are accounted for primarily outside the agricultural sector (transport, energy, buildings). In this study, we have reviewed options, impacts, externalities, and accounting issues of energy mitigation options from agriculture. Furthermore, we have estimated global and regional mitigation potentials from agriculturally driven energy efficiency improvements.

Energy consumption and greenhouse gas emissions are closely linked. Agricultural operations can save energy by changing the volume and mix of produced commodities and by reducing energy intensities—the

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amount of energy used per unit of commodity. Together these options yield a heterogeneous and complex set of strategies that involves technological, economic, and cultural aspects. Heterogeneity results from a large number of available options and from a high spatial variation within these options. Complexity, on the other hand, results from strong interdependencies between different options and from cross-sectoral impacts. Agricultural strategies to mitigate environmental and other externalities have received increasing attention in recent decades. The importance of energy-related mitigation strategies is evident from the increasing number of refereed scientific publications. A title search with the *ISI web of knowledge* for the string “energy intensity”, “energy efficiency”, or “energy balance” returns 912 articles on agricultural topics with a record of 69 articles published in 2007. The majority of these studies, however, addresses farm level implications[1] and do not focus on the greenhouse gas emission or energy security impacts.

The objective of this paper is to examine the complex interdependencies between agriculture, energy, and greenhouse gas emissions and to put greenhouse gas emission mitigation through improved energy efficiencies in perspective with other mitigation strategies. To do so, we have divided this paper in three major parts. The first part describes available agricultural options to decrease net fossil energy use. The following part discusses the complex relationship between agricultural energy options and net greenhouse gas emissions and addresses important accounting issues. Finally, we use empirical data to compute and compare potentials to improve agricultural energy use across different international regions.

Agricultural options to decrease net energy consumption

To systematize agricultural options for the reduction of energy use, several general characteristics can be employed. These characteristics relate to the nature and relative position of energetic improvements and distinguish (1) production vs. consumption, (2) technical progress vs. technical substitution, (3) on-farm vs. off-farm, and (4) market vs. non-market strategies. In presenting and classifying these options, we first address technical progress involving both agricultural inputs and outputs. Subsequently, we discuss possible energy savings through input substitution in agricultural production. Finally, we explain the impact of changes on the demand side.

Technical progress in agriculture

Technical progress can be achieved with respect to the energy efficiency of all major inputs. Principal strategies include plant and livestock genetic improvements (Koch 2007), more efficient machinery (Glancey and Kee 2003), improved agro-chemicals (Yu et al. 2006), and more efficient irrigation systems (Sakellariou-Makrantonaki et al. 2007). Plant breeding and genetic engineering increase yields, reduce input requirements, or increase the resistance to stress from pests, water, temperature, and various physical or chemical soil conditions. Furthermore, genetic modifications may improve product quality and thus decrease energy requirements for subsequent processing. Machinery-related energy savings are possible through higher fuel efficiencies, lower technical losses, i.e. during harvest, and improved input use efficiencies (Olk et al. 1999). The last strategy includes precision cropping (Robert 2002) with site specific management of nutrients (Dobermann et al. 2002), pesticides, and water; as well as computer controlled livestock feeding in intensive systems. Other improvements of fertilizer and pesticides may result in increased yields or reduced yield losses.

Technical progress on the production side also involves bioenergy and biomaterial strategies (van Beilen and Poirier 2007). A large spectrum of dedicated energy crops, plant residues, livestock manure, and by-products of agricultural commodity processing could be converted into energy or industrial material, thereby reducing the consumption of and dependency on fossil energy (Lieffering et al. 2008). Current research to develop novel bioenergy and biomaterial technologies includes options to convert cellulose into biofuels (second generation biofuels) and to establish improved crop varieties for the production of industrial oils and biopolymers.

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[1] An additional search within the 912 title for at least one match of the topics “CO_2-balance”, “carbon balance”, “greenhouse gas”, “carbon emission”, or “emission mitigation” returned only seven matches.

Examples of relatively new bioenergy and biomaterial applications include the potential use of Crambe for industrial oils (Capelle and Tittonel 1999), Guayule for biopolymers (van Beilen and Poirier 2007), and Jatropha for biodiesel (Kaushik et al. 2007).

The speed of technical progress in agriculture depends on market and political incentives for research (Raitzer and Kelley 2008; Traxler and Byerlee 2001), on the existence and distance to biophysical limits (Beadle and Long 1985; Bugbee and Salisbury 1988), and on individual achievements (Hughes 1987). The adoption of novel technologies is a function of economic incentives, infrastructure and market constraints (Roos 1998), the status of involved individuals and institutions (Podolny and Stuart 1995), and producer and consumer preferences and their acceptance of novel products (Bruhn 2007).

Input substitution in agriculture

Agricultural energy consumption can also be reduced with existing technologies through substitution of inputs (Edwards et al. 1996). Note that there is a fundamental difference between the economic interpretation of technical progress and input substitution. While the former shifts a production possibility frontier for a given input endowment outward, the latter involves movements along a given frontier. Input substitutions are driven by economic conditions, foremost by the cost of energy. If the relative price for energy increases, the overall energy intensity at a given production level will fall (Ramsden et al. 1999). However, the resulting substitution effects can be complex because energy is contained in almost all agricultural inputs to varying degrees.

Possible input substitution options involve changes in irrigation, tillage (Rathke et al. 2007), fertilization (Tzilivakis et al. 2005), crop protection intensities (Deike et al. 2008), and level of mechanization (Nkakini et al. 2006); the early retirement of fuel inefficient machinery, the choice of energy efficient crop and livestock breeds (Sabri et al. 1991), and livestock management alternatives related to feeding (Chen 2001), housing, and manure treatment (Amon et al. 2001). Energy-friendly fertilization systems also include the reduction of nitrogen fertilizer requirements through legume rich rotations. Note that the intensification of irrigation, fertilization, and crop protection, while likely to increase the energy use per hectare, can decrease the energy intensity per unit of product if crop yields increase sufficiently (Tzilivakis et al. 2005). Under certain conditions, however, a more extensive use of these inputs may improve the energy intensity. Reduced tillage systems generally decrease both energy levels per hectare and per unit of product. Further energy savings may be achieved through adoption of agricultural system designs with reduced transportation needs and substitution of traditional energy sources at farm level with renewable sources.

Demand changes for agricultural commodities

Agricultural commodities are processed into food, livestock feed, fiber, or energy. Demand curves for these commodities influence the total volume of production and thus, the total amount of energy used in agriculture. There are two basic strategies to save energy. One major strategy involves changes in human diets towards food that is rawer, more local, more vegetarian, more seasonal, and based on energy-friendlier crop management. Particularly, seasonal and raw food saves energy for storage and processing, respectively. Local food saves energy for transportation and handling. In addition, the consumption of local fruits and vegetables also implies reduced energy intensities via reduced plant protection and increased yields[2]. Vegetarian food does not have metabolic energy losses as have animal foods (Chen 2001; Eshel and Martin 2006). A second important strategy relates to demand for renewable energy and products.

Demand-based strategies are driven by market prices, policies, and cultural preferences (Ackerman and Tellis 2001; Getz and Brown 2006). Higher energy prices increase the wedge between energy friendly and energy intensive commodities and thereby shift consumption towards the former. Policies can affect energy prices and stimulate the production of energy-friendly commodities. These stimulations may also result from the removal of trade barriers. Environmental policies which affect land availability, i.e. protection of old growth forests, wetlands, or other nature

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[2] Fruits and vegetables for distant markets are usually harvested earlier and more pesticides have to be used to avoid spoilage.

reserves, increase the value of land and therefore the price of land intensive commodities. This implies potential energy savings through an increase in the share of vegetarian food and through less overall food consumption. Private or public efforts for a healthier human diet may—especially in developed countries—result in energy savings through reduced meat consumption. However, energy savings through vegetarian diets face several limitations. First, animal foods are an important source of lipids and proteins, which are needed for a healthy human diet. Second, some land qualities, while suitable for grazing regimes with ruminant animals, may not be suitable for the cultivation of food crops. Third, livestock production meets simultaneous demands for food and non-food products such as fiber, leather, and other commodities.

Greenhouse gas impacts of improved energy management in agriculture

Reduced fossil energy combustion decreases CO_2 emissions. For individual energy sources, the magnitude of CO_2 emissions is fairly well known and CO_2 savings from agricultural energy mitigation options depend on the regionally specific mix of primary energy sources (Alcantara and Roca 1995). However, the direct CO_2 benefits are linked to a number of important indirect impacts, which may amplify or diminish the net greenhouse gas emission savings. Many of these indirect impacts are uncertain or unknown. To understand the complex relationship between agricultural energy management and greenhouse gas emissions, the remainder of this section addresses the indirect greenhouse gas impacts and relates them to several important accounting issues.

First, indirect greenhouse gas impacts include impacts beyond the CO_2 contained in fossil energy. Particularly, improved livestock manure management which reduces fossil energy consumption may simultaneously decrease methane and nitrous oxide emissions (Monteny et al. 2006; van der Meer 2008). Dedicated bioenergy plantations may considerably increase nitrous oxide emissions through fertilization (Crutzen et al. 2008) but decrease overall livestock emissions because rising land prices make land intensive products less competitive (Schneider and McCarl 2003). Energy reductions through land management changes related to tillage, fertilization, and irrigation affect soil carbon levels and nitrous oxide emissions (Ellert and Janzen 2008; Liu et al. 2007).

Second, rising greenhouse gas concentrations are a global externality and greenhouse gas impacts should therefore be evaluated at the global level. Such an assessment, however, should avoid simple summing of independent estimates (Schneider and McCarl 2006). In a complex world with specialized, interdependent industries, intensive international trade relations, and limited resources, agricultural emissions may leak across space, time, technologies, economic sectors, and greenhouse gases (Schneider and Kumar 2008). These additional emissions, due to agricultural responses elsewhere, also include potential emissions from land use changes including deforestation (Cowie et al. 2007; Schneider et al. 2008). The magnitude of emission leakage depends on the regional scope, political treatment, land intensity, and commodity supply impacts of agricultural mitigation strategies (Lee et al. 2007). For example, political support for specific dedicated bioenergy technologies in suitable agricultural areas of selected countries has a high leakage potential and can more than offset the direct gains (Searchinger et al. 2008). On the other hand, if improved fossil energy efficiency increases agricultural commodity supply per hectare, external greenhouse gas emission mitigation benefits may occur.

Third, unbiased accounting must simultaneously cover both agricultural and linked non-agricultural sectors. For example, farmers' options to save energy contained in synthetic fertilizer involve the type and quantity of the fertilizers applied to fields. Options in the fertilizer manufacturing sector save energy requirements per unit of fertilizer. In reality, both things happen simultaneously. Higher costs of fossil energy would cause farmers to apply less fertilizer and manufacturers to use less energy per unit of fertilizer. Sector independent assessments of reduction potentials would therefore overstate the true mitigation potential because of two biases. On one hand, the farm assessment would apply excessive embedded energy coefficients per unit of fertilizer and the manufacturing assessment would apply energy savings to basic fertilizer consumption levels.

Fourth, direct and indirect greenhouse gas emission impacts differ across farm locations because of variations in soil, climate, and economic conditions. Adequate estimation of agricultural mitigation

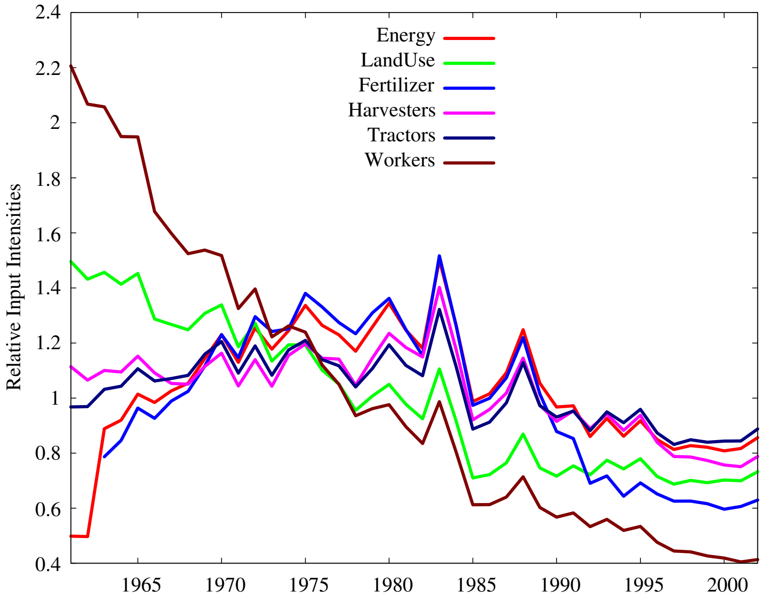

Fig. 1 Input intensities over time relative to average input intensity between 1961 and 2003 aggregated over all developed countries

potentials from increased energy efficiencies should account for this heterogeneity (Antle et al. 2004; De Cara and Jayet 2000). Fifth, energy savings should be related to their effects on commodity production, i.e. on levels of production of good and services. The majority of farm energy studies compares the ratio of biomass output to fossil energy input between alternative management options, where the input also includes off-farm energy uses (Deike et al. 2008; Gundogmus 2006; Hoeppner et al. 2006; Kaltsas et al. 2007; Mendoza 2005). However, none of these detailed studies considers the implications on total commodity production in a region and their potential leakage effects as described above.

Sixth, improvements in agricultural energy efficiencies typically refer to changes beyond business as usual and require specific investment, education, or technical progress. There are substantial differences between technical and economic potentials to save energy and greenhouse gases (Schneider and McCarl 2003; Smith et al. 2007b). Technical potentials give energy and emission impacts under maximum adoption of particular strategies, irrespective of costs. Economic potentials estimate the achievable fraction of technical potential at given cost levels. Note that full cost accounting requires consideration of investment costs, variable operational costs, opportunity costs, market prices, non-market externalities, and transaction costs.

International energy mitigation potentials

In this section, we use a simple energy budgeting to estimate greenhouse gas emission savings from increased energy efficiencies[3]. We multiply FAO-based country level data on agricultural inputs and production with energy coefficients from the scientific literature to approximate input and output energy. The ratio of total energy input to total energy output yields a measure of energy intensity, which is computed across countries and years. Subsequently, we estimate energy and greenhouse gas emission reduction potentials related to improved energy efficiency. Our approach is crude for several reasons. First, we do not explicitly account for the impact of climate and land quality on agricultural energy intensities. Second, the representation of agricultural inputs is limited to three types of fertilizers, three types of pesticides, tractors and harvesting combines, and coarse land use categories. Energy and emissions from irrigation, grain drying, and human labor are not included. Third, for lack of data we use uniform energy conversion and emission coefficients across countries. Fourth, the national data from FAO we have used may differ in quality and scope across space and time. Fifth, we do not account for the above described

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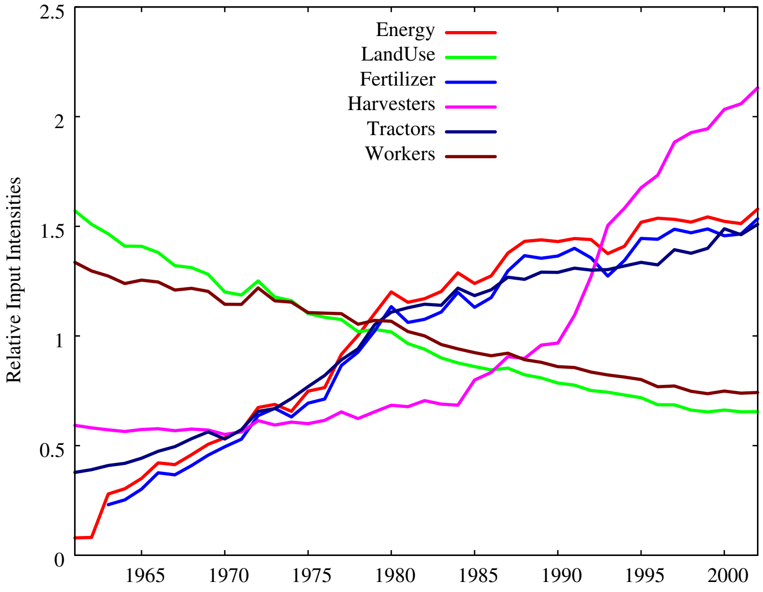
[3] While our discussion here focuses on aggregate values for eight major regions, country-specific results are available from the authors.

Fig. 2 Input intensities over time relative to average input intensity between 1961 and 2003 aggregated over all developing countries

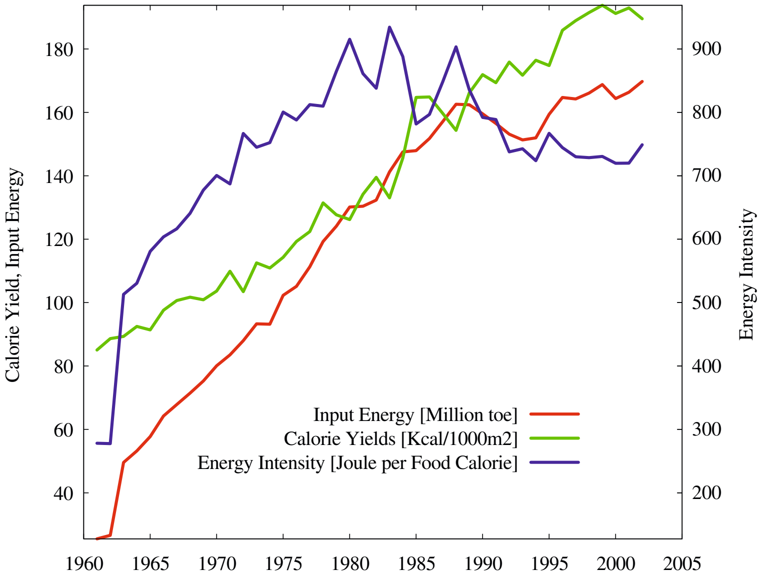


emission externalities. While the omission of land quality and climate impacts is likely to overstate potential energy mitigation potentials, the direction of the impact of the other limitations on the results is difficult to assess.

Agricultural intensities are commonly reported as per-hectare values. Here, we relate energy contained in agricultural inputs to food calorie output. Thus, high input agricultural systems with high yields can have a relatively low energy intensity. Similarly, low input systems with low yields can have a relatively high energy intensity. Changes in input intensities over time are displayed in Fig. 1 for developed countries and for developing countries in Fig. 2.

We find similar rates of land intensity reductions, which reflect similar crop and livestock yield improvements. Agricultural labor intensities have decreased in most countries but at substantially higher rates in developed countries. Fertilizer consumption and machinery use intensities have steadily increased in developing countries. In developed countries, we find declining intensities after the mid 1980s. The net effect

Fig. 3 Global development of energy input, food energy output (*left axis*), and input energy intensities (*right axis*), *Toe* tons of oil equivalent



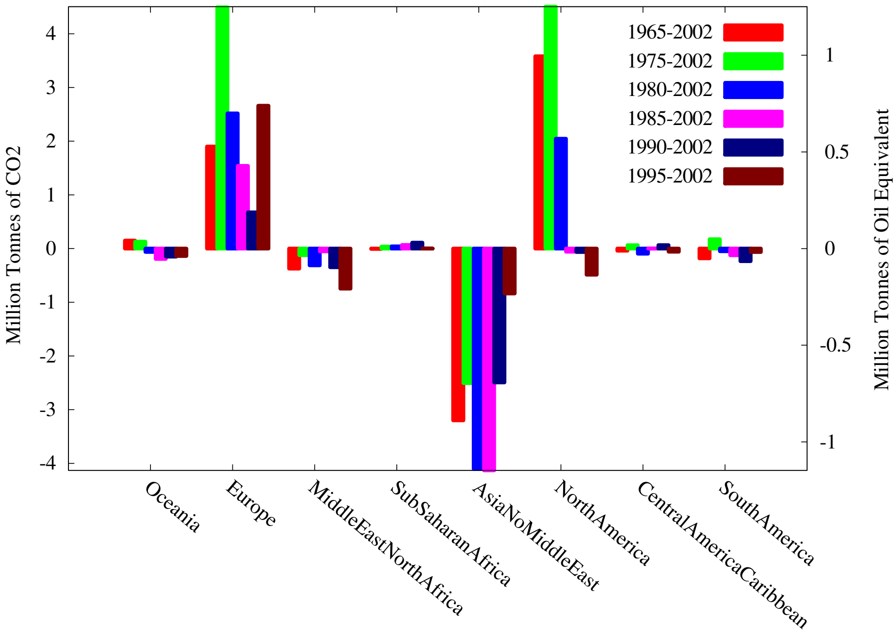


Fig. 4 Average annual greenhouse gas and energy savings due to development. Values are computed by (1) multiplying the difference between the 3-year average energy intensity of earlier years (1964–66, …, 1994–96) and that of 2000–02 with the annual average food energy output of 2000–02, (2) summing over individual countries into region groups, (3) converting energy values into carbon and oil equivalents, and (4) dividing by the number of years between the comparison periods

on energy intensities also differs between developed and developing countries. While the former show decreasing energy requirements per calorie, energy intensities in developing countries are rising. Globally aggregated trends in input energy, calorie yields, and energy intensities are displayed in Fig. 3. From the early 1960s to the mid 1980s, we find that rising yields resulted in increasing energy intensities. Since then, yields have been growing with on average decreasing energy intensities.

The net impact of development on energy intensities and carbon emissions for different regions is shown in Fig. 4. The most recent comparison between 1995 and 2002 reveals emission savings only for

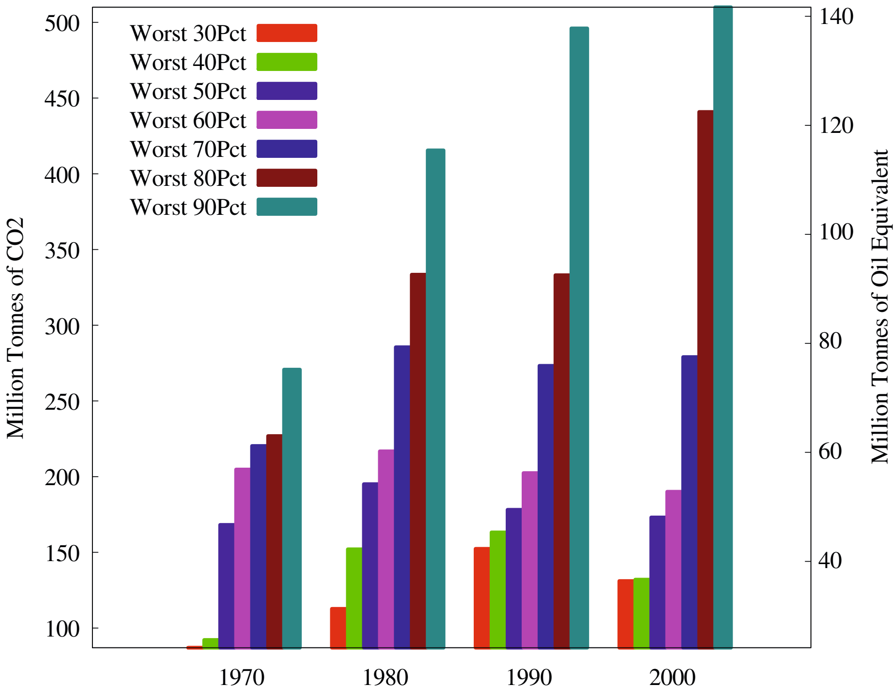


Fig. 5 Estimated global carbon and energy savings potential by improving average national agricultural input energy efficiencies to levels observed in other countries. The columns assume that a certain fraction of the worst countries reduce input energy intensities to the level of the country at the border of this fraction. Particularly, “Worst 50 Pct” implies that all areas in countries with below average input use efficiency improve to the level of the country with average efficiency

Europe, with highest contributions from Russia (35%), Germany (28%), Ukraine (21%), and France (14%). Asian countries, on the other hand, continue to increase agricultural energy use, although with decreasing rates. Particularly, in India and China, the increasing energy input from agrochemicals is not matched by the increase in commodity yields.

Global technical potentials to save energy through improved use of agricultural inputs are shown in Fig. 5. We distinguish seven scenarios, which reflect different assumptions about the achievability of energy intensity targets. In particular, for each scenario, we compute national energy savings as the difference between current energy intensity and intensity target times the national food energy output. The global savings potential is calculated by summing national savings over all countries, where the actual energy intensity is above (worse than) the target intensity (Table 1).

To place the scenario assumptions in perspective, Table 2 lists energy, labor, and land intensities for all threshold countries, i.e. those countries which define the energy intensity target for a given scenario. The differences in energy intensities between countries are

Table 1 Energy, labor, and land intensities of scenario threshold countries

Scenario	Threshold country	1970	1980	1990	2000
Worst	Name	Australia	USA	China	Australia
30 Pct	Energy intensity (KJ/Kcal)	889.63	1,033.10	729.63	689.09
	Labor intensity (#/Gcal)	17.47	8.36	571.36	5.80
	Land intensity (cal/m2)	11.99	238.65	274.91	33.21
	Animal food share (%)	12	7	5	7
Worst	Name	Canada	Australia	Iran	India
40 Pct	Energy intensity (KJ/Kcal)	857.08	849.08	695.18	686.27
	Labor intensity (#/Gcal)	20.38	13.67	249.67	507.69
	Land intensity (cal/m2)	129.77	14.33	120.70	594.55
	Animal food share (%)	9	9	6	7
Worst	Name	Venezuela	China	Australia	Mexico
50 Pct	Energy intensity (KJ/Kcal)	427.28	662.89	648.80	590.16
	Labor intensity (#/Gcal)	426.69	733.45	9.18	142.06
	Land intensity (cal/m2)	37.21	232.87	21.86	152.30
	Animal food share (%)	14	4	7	9
Worst	Name	Pakistan	South Africa	USA	USA
60 Pct	Energy intensity (KJ/Kcal)	241.53	596.30	577.94	553.52
	Labor intensity (#/Gcal)	713.37	94.55	4.45	3.44
	Land intensity (cal/m2)	241.90	80.30	404.28	444.03
	Animal food share (%)	11	4	5	6
Worst	Name	Angola	Mexico	Brazil	Bangladesh
70 Pct	Energy intensity (KJ/Kcal)	185.44	401.30	452.01	418.11
	Labor intensity (#/Gcal)	878.26	188.49	129.16	632.07
	Land intensity (cal/m2)	8.68	141.64	109.65	1,338.13
	Animal food share (%)	3	7	7	2
Worst	Name	India	Sudan	Sudan	Zambia
80 Pct	Energy intensity (KJ/Kcal)	163.56	285.23	354.65	191.74
	Labor intensity (#/Gcal)	713.43	822.86	1,436.83	1,245.72
	Land intensity (cal/m2)	295.04	15.40	9.78	16.42
	Animal food share (%)	4	12	21	4
Worst	Name	Mali	Thailand	Nigeria	Ivory Coast
90 Pct	Energy intensity (KJ/Kcal)	48.31	112.97	110.18	101.37
	Labor intensity (#/Gcal)	1,086.89	331.89	307.55	326.11
	Land intensity (cal/m2)	15.05	474.41	166.85	120.02
	Animal food share (%)	8	2	1	9

Table 2 General assumptions to compute agricultural energy intensities

Parameter	Value	Sources
Energy content of pesticides	101 GJ per tonne	Heyland and Solansky (1979)
Energy content of nitrogen fertilizer	48 GJ per tonne	
Energy content potassium fertilizer	7.9 GJ per tonne	Siegel (1979)
Energy content phosphate fertilizer	4.8 GJ per tonne	
Annual tractor energy	2,206 l per year 85 GJ per tractor	Own computations based on agricultural machinery inventory and diesel consumption statistics for Denmark (Landøkonomisk Oversigt 1999)
Annual harvester energy	1,195 l per year 46 GJ per harvester	
Energy content of crop and livestock products	cal per 100 g	Food and Agricultural Organization (2008)
Diesel emissions	86 kg CO2/GJ	Department for Transport (2008)
Diesel energy	38.6 MJ/l	

large. The country at the worst 30% threshold uses between seven and 18 times more energy per food calorie than the country at the worst 90% threshold. Furthermore, the energy intensities do not exhibit a strong correlation with land and labor productivities. Labor intensities range between three (USA 2000) and 1,400 (Sudan 1990) workers per Giga calories. Similarly, land intensities span nine (Angola 1970, Sudan 1990) to 1,300 (Bangladesh 2000) calories per square meter.

The total energy consumption in 2000 has been estimated at about 10 billion tons of oil equivalent (EIA 2008). Thus, a reduction in agricultural energy requirements of 100 million tons of oil equivalent would diminish energy consumption by about 1%. However, to reach annual savings of this magnitude (Fig. 4), an energy efficiency somewhere between that of Bangladesh and Zambia in 2000 would be required in all countries (Table 2). If one chooses the more feasible scenario,

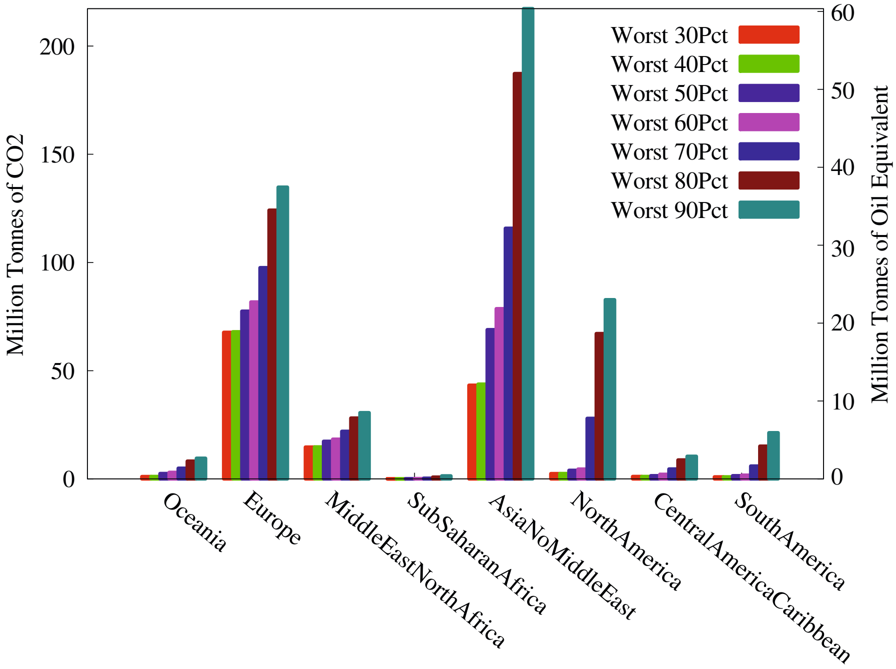


Fig. 6 Regional distribution of global carbon savings from Fig. 5 for year 2000

where all below-average countries increase their energy efficiency to the current global average, the annual savings would amount to 50 million tons of oil equivalent, or 0.5% of global energy consumption. Figure 5 also shows the implied carbon savings from improved energy efficiencies. For lack of better data, we derived carbon savings through energy and emission coefficients of diesel (Table 2). The regional distribution of energy and carbon savings is displayed in Fig. 6. We find that the bulk of improvement potentials occurs in Europe and Asia while North American agriculture already has a relatively high energy efficiency.

Conclusions

Efforts to reduce greenhouse gas emissions from fossil energy use serve two principal objectives: (1) mitigation of climate change and (2) improvement of energy security. Agricultural energy abatement strategies are as diverse and complex as are agricultural management alternatives. In its fourth assessment, the authors of the agricultural chapter for IPCC working group III (Smith et al. 2007a) did not include emission mitigation potentials from increased energy efficiency, in order to avoid double counting, since efficiency increases are accounted for primarily outside the agricultural sector (transport, energy, buildings). In this study, we have reviewed options, impacts, externalities, and accounting issues of energy mitigation options from agriculture. Furthermore, we have estimated global and regional mitigation potentials from agriculturally driven energy efficiency improvements. The implied mitigation strategies include private and public funding for agricultural research and development, and adoption of existing management alternatives with lower energy intensities. We find that global agricultural energy intensities increased until the 1980s and slightly decreased thereafter. Thus, a continuation along the historical trend does not imply large energy or emission savings in the near future. While the variation in energy intensities over the last 30 years has been relatively small, large differences exist between countries. A considerable portion of that variation may be due to differences in agricultural management. Our coarse results suggest under year 2000 conditions possible savings up to 150 million tons of oil equivalent or about 500 million tons of carbon emissions. However, a more detailed statistical analysis and better data would be needed to exclude the impact of natural conditions from these potentials.

Technical mitigation potentials say little about their economic feasibility. Under business as usual conditions, there is little likelihood that farmers will adopt energy saving strategies. To realize greenhouse gas emission mitigation potentials, the associated strategies must become cost-efficient at farm level, either through market price changes or through policies. From a social point of view, cost-efficient adoption of agricultural mitigation strategies would require an efficient internalization of the climate and other relevant externalities related to biodiversity, landscape, and security of food and water. To avoid emission leakage, such an internalization must occur at the global level. Furthermore, energy efficiency potentials must be jointly considered with all other strategies to account for synergies and trade-offs.

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