Greenhouse Gas Emission Mitigation and Energy Intensities in 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 the past decades, while increasing yields, led to lower average energy efficiencies between the sixties and mid eighties. In the last two decades, energy intensities in developed countries increased, however, with little impact on greenhouse gas emissions. Efficiency differences across countries suggest a maximum improvement potential of 500 million tons of CO_2 annually.

Keywords

Energy intensity, Agriculture, Greenhouse gas emissions, Mitigation potential, Fertilizer efficiency

Introduction

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 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 sector crossing 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[2] 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, the paper is structured as follows. In section 2, we describe qualitatively available agricultural options to decrease net fossil energy use. Section 3 discusses the complex relationship between agricultural energy options and net greenhouse gas emissions and addresses important accounting issues. Section 4 uses empirical data to compare potentials to improve agricultural energy use across different international regions. Section 6 concludes.

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 a) production vs. consumption, b) technical substitution vs. technical progress, c) on-farm vs. off-farm, and d) 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 the agricultural production. Finally, we explain the impact of changes on the demand side.

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[2] 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 7 matches.

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. Other improvements of fertilizer and pesticides may result in increased yields or reduced yield losses.

Technical progress on the production side also involves bio-energy and bio-material 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 bio-energy and bio-material technologies includes options to convert cellulose into bio-fuels (2nd generation bio-fuels) and to establish improved crop varieties for the production of industrial oils and bio-polymers. Examples of relatively new bioenergy and biomaterial applications include the potential use of Crambe for industrial oils (Capelle and Tittonel 1999), Guayule for bio-polymers (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 to a certain extent also on unpredictable individual achievements. The adoption of novel technologies is a function of market prices, infrastructure and market constraints (Roos 1998), 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 at 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). 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.

Demand changes for agricultural commodities

Agricultural commodities are processed into food, 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. The demand is driven by market prices, cultural preferences, and policies (Ackerman and Tellis 2001;Getz and Brown 2006). These drivers can promote two fundamentally different 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[3]. 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. High tax differences between fossil and renewable energy can provide sufficient economic incentives for agriculture to produce substitutes for fossil fuel based products on a large-scale.

The most important driver on the demand side is the relative price of energy. Higher energy prices increase the wedge between energy friendly and energy intensive commodities and thereby shift consumption towards the former. A variety of other factors, however, affects the energy reduction potential on the demand side. Policies to protect nature reserves such as old growth forests and wetlands, 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. In developing countries, efforts towards a healthy diet require an increased food consumption with higher shares in protein and lipids leading to higher levels of energy consumption.

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

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 and intensive international trade relations, agricultural energy management may leak emissions 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 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 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.* 2007). 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 empirically estimate greenhouse gas savings from increased energy efficiencies. We use FAO based country level data on agricultural inputs and production, and energy coefficients from the scientific literature to derive measures of energy intensity across space and time. 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 is not included. Third, for lack of data we use uniform energy conversion and emission coefficients across countries. Fourth, the employed national data from FAO may differ in quality and scope across space and time. Fifth, we do not account for the above described emission externalities.

Changes of yields and input intensities over time are displayed in Figure 1 for developed countries and for developing countries in Figure 2. We find similar rates of land intensity reductions, which are driven by calorie yield improvements per hectare and total agricultural area changes. Agricultural labor intensities, on the other hand, have decreased at higher rates in developed countries. Fertilizer consumption and machinery use intensities have been steadily increasing in developing countries. In developed countries, we find a reduction after the mid eighties. The net effect 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 Figure 3. From the early 1960'ies to the mid-eighties we find that rising yields resulted in increasing energy intensities. Since then yields have been growing with perhaps slightly decreasing energy intensities. The net impact of development on energy intensities and carbon emissions for different regions are shown in Figure 4. The most recent comparison reveals emission savings only for Europe. Asian countries, on the other hand, continue to increase agricultural energy use, although with decreasing rates. Global technical potentials to save energy through improved use of agricultural inputs are shown in Figure 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 actual 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. 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 large. The country at the worst 30% threshold uses between 7 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 3 (USA 2000) and 1400 (Sudan 1990) workers per Giga calories. Similarly, land intensities span 9 (Angola 1970, Sudan 1990) to 1300 (Bangladesh 2000) calories per square meter. The total energy consumption in 2000 has been estimated at about 10 billion tons of oil equivalent (International Energy Agency, 2008). Thus, a reduction in agricultural energy requirements of 100 million tons of oil equivalent would diminish energy consumption by about 1 percent. However, to reach annual savings of this magnitude (Figure 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, 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 percent 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 1). The regional distribution of energy and carbon savings is displayed in Figure 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: a) mitigation of climate change and b) improvement of energy security. Agricultural energy abatement strategies are as diverse and complex as are agricultural management alternatives. In its fourth assessment report of working group III, the authors of the agricultural chapter (Smith et al. 2007) did not include emission mitigation potentials from increased energy efficiency. The main argument was that such efficiency increases occur primarily outside the agricultural sector. In this study, we address this argument and review options, impacts, externalities, and accounting issues of energy mitigation options from agriculture.

Furthermore, we estimate global and regional mitigation potentials from agriculturally driven energy efficiency improvements. We find that global agricultural energy intensities have been increasing until the eighties and slightly decreasing thereafter. Thus, the basic trend does not imply large energy or emission savings in the near future. However, 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 possible savings up to 150 million tons of oil equivalent or about 500 million tons of carbon emissions. However, a more detailed statistical analysis is 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 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.

References

Ackerman, D. and Tellis, G. (2001). Can culture affect prices? A cross-cultural study of shopping and retail prices. *Journal of Retailing* 77, 57-82.

Alcantara, V. and Roca, J. (1995). Energy and Co2 Emissions in Spain - Methodology of Analysis and Some Results for 1980-90. *Energy Economics* 17, 221-230.

Amon, B., Amon, T., Alt, C., Moitzi, G., and Boxberger, J. (2001). Nitrous oxide emissions from cattle production systems and mitigation options. *Phyton-Annales Rei Botanicae* 41, 17-28.

Antle, J. M., Capalbo, S. M., Elliott, E. T., and Paustian, K. H. (2004). Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO2 fertilization: An integrated assessment approach. *Climatic Change* 64, 289-315.

Beadle, C. L. and Long, S. P. (1985). Photosynthesis -- is it limiting to biomass production? *Biomass* 8, 119-168.

Bruhn, C. M. (2007). Enhancing consumer acceptance of new processing technologies. *Innovative Food Science & Emerging Technologies* 8, 555-558.

Bugbee, Bruce G. and Salisbury, Frank B. (1988). Exploring the Limits of Crop Productivity : I. Photosynthetic Efficiency of Wheat in High Irradiance Environments. *PLANT PHYSIOLOGY* 88, 869-878.

Capelle, A. and Tittonel, E. D. (1999). Crambe, a potential non food oil crop. I Production. *Agro Food Industry Hi-Tech* 10, 22-27.

Chen, D. W. (2001). Environmental challenges of animal agriculture and the role and task of animal nutrition in environmental protection - Review. *Asian-Australasian Journal of Animal Sciences* 14, 423-431.

Cowie, A., Schneider, U. A., and Montanarella, L. (2007). Potential synergies between existing multilateral environmental agreements in the implementation of land use, land-use change and forestry activities. *Environmental Science & Policy* 10, 335-352.

Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W. (2008). N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics* 8, 389-395.

De Cara, S. and Jayet, P. A. (2000). Emissions of greenhouse gases from agriculture: The heterogeneity of abatement costs in France. *European Review of Agricultural Economics* 27, 281-303.

Deike, S., Pallutt, B., and Christen, O. (2008). Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity. *European Journal of Agronomy* 28, 461-470.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H. C., Nagarajan, R., Satawathananont, S., Son, T. T., Tan, P. S., Wang, G. H., Chien, N. V., Thoa, V. T. K., Phung, C. V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G. C., and Adviento, M. A. A. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* 74, 37-66.

Edwards, B. K., Howitt, R. E., and Flaim, S. J. (1996). Fuel, crop, and water substitution in irrigated agriculture. *Resource and Energy Economics* 18, 311-331.

Ellert, B. H. and Janzen, H. H. (2008). Nitrous oxide, carbon dioxide and methane emissions from irrigated cropping systems as influenced by legumes, manure and fertilizer. *Canadian Journal of Soil Science* 88, 207-217.

Eshel, G. and Martin, P. A. (2006). Diet, energy, and global warming. *Earth Interactions* 10.

Getz, D. and Brown, G. (2006). Critical success factors for wine tourism regions: a demand analysis. *Tourism Management* 27, 146-158.

Glancey, James L. and Kee, Edwin (2003). Technical and strategic advances in mechanization. *Hortscience* 38.

Gundogmus, E. (2006). Energy use on organic farming: A comparative analysis on organic versus conventional apricot production on small holdings in Turkey. *Energy Conversion and Management* 47, 3351-3359.

Heyland, K. U. and Solansky, S (1979). Energieeinsatz und Energieumsetzung im Bereich der Pflanzenproduktion. *Agrarwirtschaft und Energie, Berichte über die Landwirtschaft* 15-30.

Hoeppner, J. W., Entz, M. H., McConkey, B. G., Zentner, R. P., and Nagy, C. N. (2006). Energy use and efficiency in two Canadian organic and conventional crop production systems. *Renewable Agriculture and Food Systems* 21, 60-67.

International Energy Agency (IEA) Statistics Division. 2006. Energy Balances of OECD Countries (2006 edition) and Energy Balances of Non-OECD Countries (2006 edition). Paris: IEA. Available at http://data.iea.org/ieastore/default.asp.

Kaltsas, A. M., Mamolos, A. P., Tsatsarelis, C. A., Nanos, G. D., and Kalburtji, K. L. (2007). Energy budget in organic and conventional olive groves. *Agriculture Ecosystems & Environment* 122, 243-251.

Kaushik, N., Kumar, K., and Kumar, S. (2007). Potential of Jatropha curcas for biofuels. *Journal of Biobased Materials and Bioenergy* 1, 301-314.

Koch, G. (2007). The genetic basis of yield potential and breeding in sugarbeet. *Zuckerindustrie* 132, 43-49.

Lee, Heng Chi, McCarl, Bruce, Schneider, Uwe, and Chen, Chi Chung (2007). Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation. *Mitigation and Adaptation Strategies for Global Change* 12, 471-494.

Lieffering, M., Newton, P., and Thiele, J. H. (2008). Greenhouse gas and energy balance of dairy farms using unutilised pasture co-digested with effluent for biogas production. *Australian Journal of Experimental Agriculture* 48, 104-108.

Liu, X. J. J., Mosier, A. R., Halvorson, A. D., Reule, C. A., and Zhang, F. S. (2007). Dinitrogen and N2O emissions in arable soils: Effect of tillage, N source and soil moisture. *Soil Biology & Biochemistry* 39, 2362-2370.

Mendoza, T. C. (2005). An energy-based analysis of organic, low external input sustainable agriculture (LEISA) and conventional rice production in the Philippines. *Philippine Agricultural Scientist* 88, 257-267.

Monteny, G. J., Bannink, A., and Chadwick, D. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agriculture Ecosystems & Environment* 112, 163-170.

Nkakini, S. O., Ayotamuno, M. J., Ogaji, S. O. T., and Probert, S. D. (2006). Farm mechanization leading to more effective energy-utilizations for cassava and yam cultivations in Rivers State, Nigeria. *Applied Energy* 83, 1317-1325.

Olk, D. C., Cassman, K. G., Simbahan, G., Cruz, P. C. S., Abdulrachman, S., Nagarajan, R., Tan, P. S., and Satawathananont, S. (1999). Interpreting fertilizer-use efficiency in relation to soil nutrient-supplying capacity, factor productivity, and agronomic efficiency. *Nutrient Cycling in Agroecosystems* 53, 35-41.

Raitzer, D. A. and Kelley, T. G. (2008). Benefit-cost meta-analysis of investment in the International Agricultural Research Centers of the CGIAR. *Agricultural Systems* 96, 108-123.

Ramsden, S., Gibbons, J., and Wilson, P. (1999). Impacts of changing relative prices on farm level dairy production in the UK. *Agricultural Systems* 62, 201-215.

Rathke, G. W., Wienhold, B. J., Wilheim, W. W., and Diepenbrock, W. (2007). Tillage and rotation effect on corn-soybean energy balances in eastern Nebraska. *Soil & Tillage Research* 97, 60-70.

Robert, P. C. (2002). Precision agriculture: a challenge for crop nutrition management. *Plant and Soil* 247, 143-149.

Roos, A. (1998). Nontechnical barriers and driving forces to bioenergy market growth in USA, Austria and Sweden - The role of policy and market structure. *Biomass for Energy and Industry* 1154-1157.

Sabri, H. M., Wilson, H. R., Wilcox, C. J., and Harms, R. H. (1991). Comparison of Energy-Utilization Efficiency Among 6 Lines of White Leghorns. *Poultry Science* 70, 229-233.

Sakellariou-Makrantonaki, M., Papalexis, D., Nakos, N., and Kalavrouziotis, I. K. (2007). Effect of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in Central Greece. *Agricultural Water Management* 90, 181-189.

Schneider, U. A. and McCarl, Bruce. A. (2006). Appraising agricultural greenhouse gas mitigation potentials: effects of alternative assumptions. *Agricultural Economics* 35, 277-287.

Schneider, Uwe A., Havlik, Petr, Schmid, Erwin, Huck, Ingo, Obersteiner, Michael, Sauer, Timm, Llull, Chris, Skalsky, Rastislav, Balkovic, Juraj, Fritz, Steffen, Dorin, Bruno, and Leduc, Sylvan (2008). Global interdependencies between population, water, food, and environmental policies. *Environmental Science & Policy*.

Schneider, Uwe A. and Kumar, Pushpam (2008). Greenhouse Gas Mitigation through Agriculture. *Choices* 23, 19-23.

Schneider, Uwe. A. and McCarl, Bruce. A. (2003). Economic potential of biomass based fuels for greenhouse gas emission mitigation. *Environmental & Resource Economics* 24, 291-312.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F. X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319, 1238-1240.

Siegel, O. (1979). Energieeinsparung in der Pflanzenproduktion im Bereich Pflanzenernährung. *Agrarwirtschaft und Energie, Berichte über die Landwirtschaft* 135-141.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, 2007: Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, P., Martino, D., Cai, Z. C., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G. X., Romanenkov, V., Schneider, U., and Towprayoon, S. (2007). Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. *Agriculture Ecosystems & Environment* 118, 6-28.

Traxler, G. and Byerlee, D. (2001). Linking technical change to research effort: an examination of aggregation and spillovers effects. *Agricultural Economics* 24, 235-246.

Tzilivakis, J., Warner, D. J., May, M., Lewis, K. A., and Jaggard, K. (2005). An assessment of the energy inputs and greenhouse gas emissions in sugar beet (Beta vulgaris) production in the UK. *Agricultural Systems* 85, 101-119.

van Beilen, J. B. and Poirier, Y. (2007). Establishment of new crops for the production of natural rubber. *Trends in Biotechnology* 25, 522-529.

van der Meer, H. G. (2008). Optimising manure management for GHG outcomes. *Australian Journal of Experimental Agriculture* 48, 38-45.

Yu, Lizhi, Li, Dongpo, Yu, Shouneng, Zou, Jihua, Tao, Ma, and Wu, Zhijie (2006). Research advances in slow/controlled release fertilizers. *Shengtaixue Zazhi* 25, 1559-1563.

Table 1 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	85 GJ per tractor	Danish Agricultural Statistics, FAO
Annual harvester energy	46 GJ per harvester	Danish Agricultural Statistics, FAO
Energy content of crop and livestock products	cal per 100 g	FAO
Diesel emissions	86 kg CO2 / GJ	Energy Information Administration
Diesel energy	38.6 MJ / l	Energy Information Administration

Table 2 Energy, labor, and land intensities of scenario threshold countries

Scenario	Threshold Country	1970	1980	1990	2000
Worst 30Pct	Name	Australia	USA	China	Australia
	Energy intensity (KJ/Kcal)	889.63	1033.10	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 40Pct	Name	Canada	Australia	Iran	India
	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 50Pct	Name	Venezuela	China	Australia	Mexico
	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 60Pct	Name	Pakistan	South Africa	USA	USA
	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 70Pct	Name	Angola	Mexico	Brazil	Bangladesh
	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	1338.13
	Animal food share (%)	3	7	7	2
Worst 80Pct	Name	India	Sudan	Sudan	Zambia
	Energy intensity (KJ/Kcal)	163.56	285.23	354.65	191.74
	Labor intensity (#/Gcal)	713.43	822.86	1436.83	1245.72
	Land intensity (cal/m2)	295.04	15.40	9.78	16.42
	Animal food share (%)	4	12	21	4
Worst 90Pct	Name	Mali	Thailand	Nigeria	Ivory Coast
	Energy intensity (KJ/Kcal)	48.31	112.97	110.18	101.37
	Labor intensity (#/Gcal)	1086.89	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

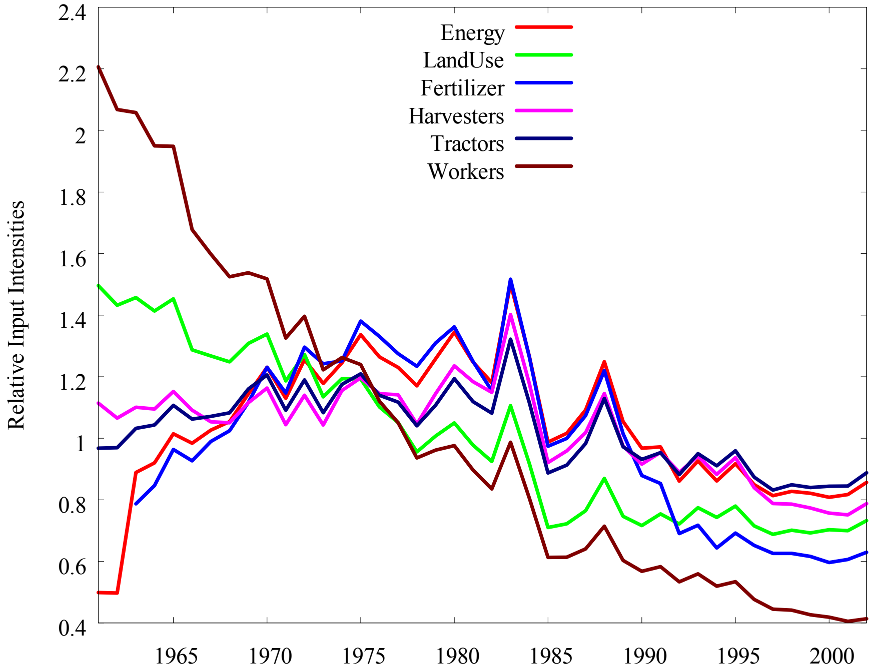

Figure 1 Input intensities over time relative to average input intensity between 1961 and 2003 aggregated over all developed countries

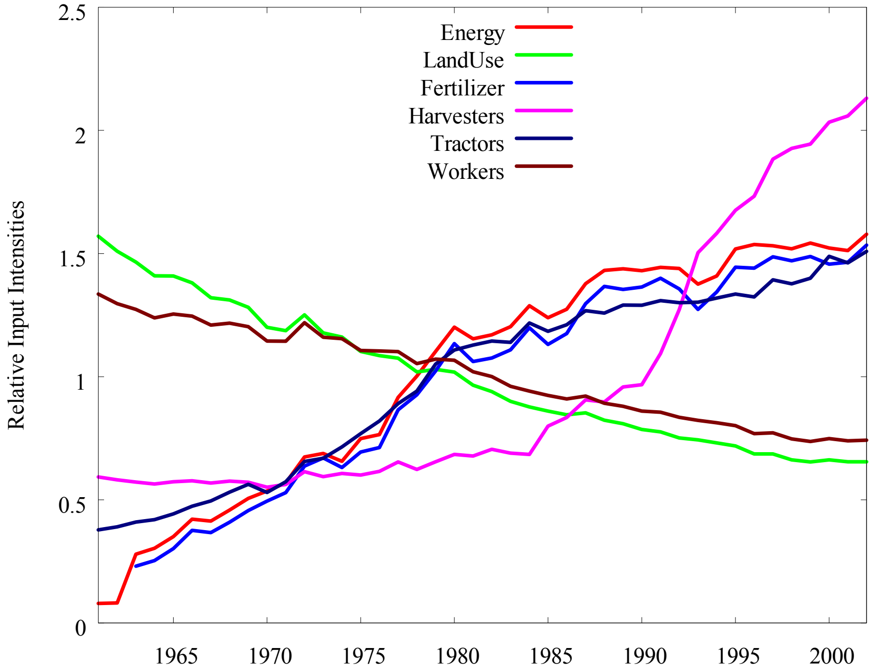

Figure 2 Input intensities over time relative to average input intensity between 1961 and 2003 aggregated over all developing countries

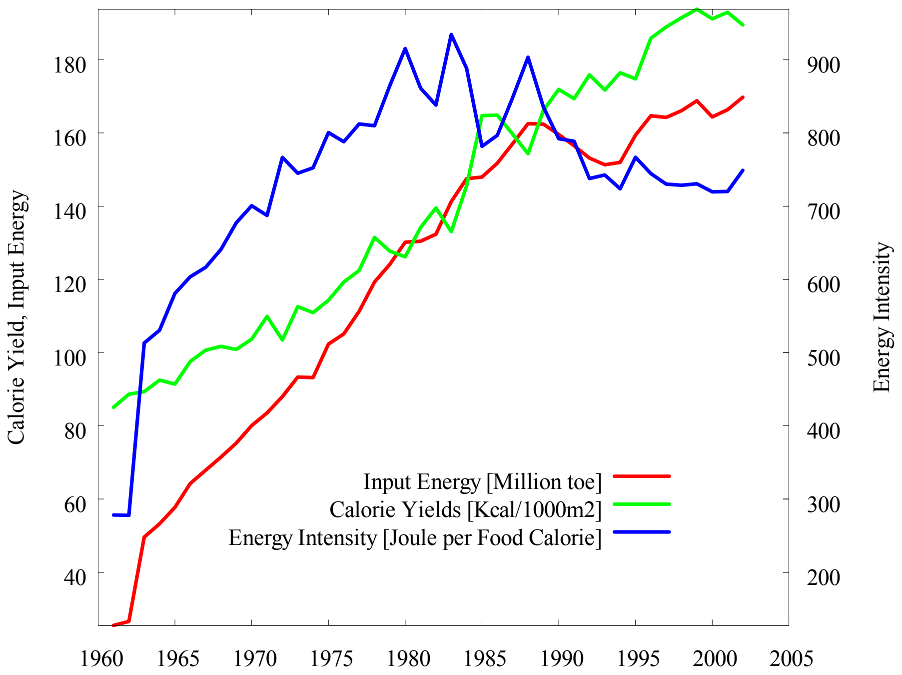

Figure 3 Global development of energy input, food energy output (left axis), and input energy intensities (right axis), [Toe = tons of oil equivalent].

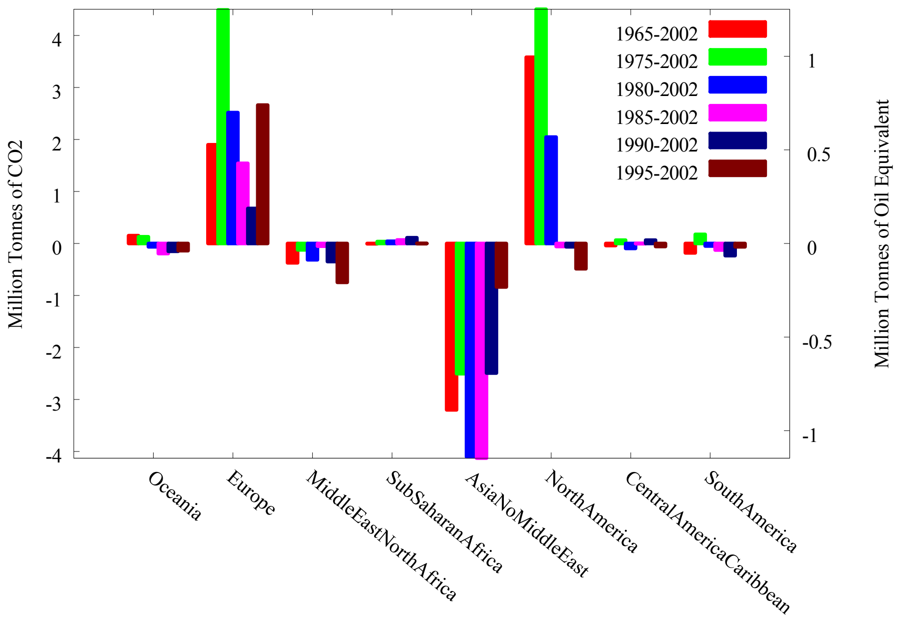

Figure 4 Average annual greenhouse gas and energy savings due to development. Values are computed by a) multiplying the difference between the three year average energy intensity of earlier years (1965, …, 1995) and that of 2000-2002 with the annual average food energy output between 2000 and 2002, b) summing over individual countries into region groups, c) converting energy values into carbon and oil equivalents, and d) dividing by the number of years between the comparison periods.

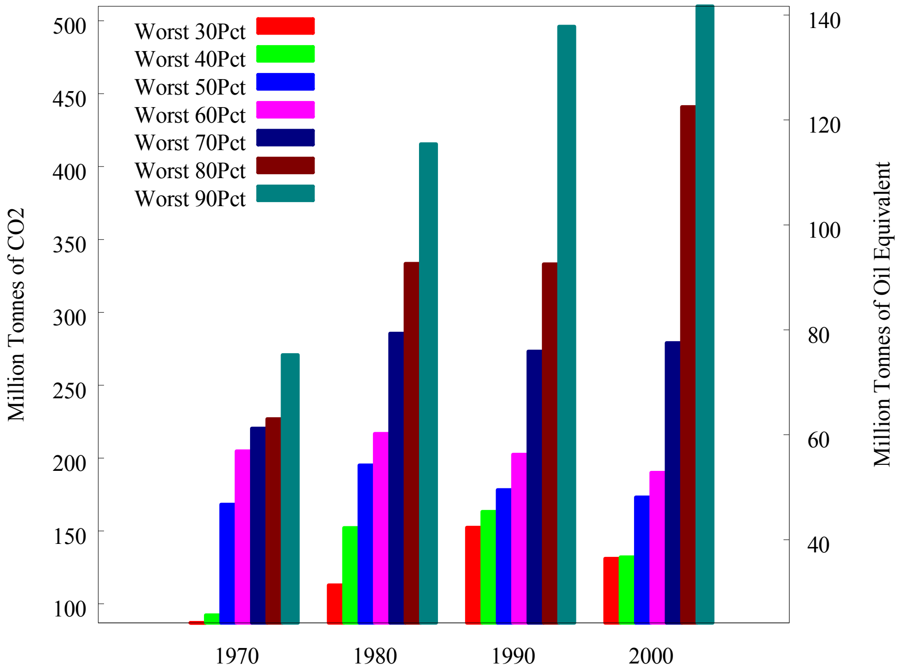

Figure 5 Estimated global carbon and energy savings potential by improving average national agricultural input energy efficiencies to levels observed in other countries. The columns assume that a certain fraction of the worst countries reduce input energy intensities to the level of the country at the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

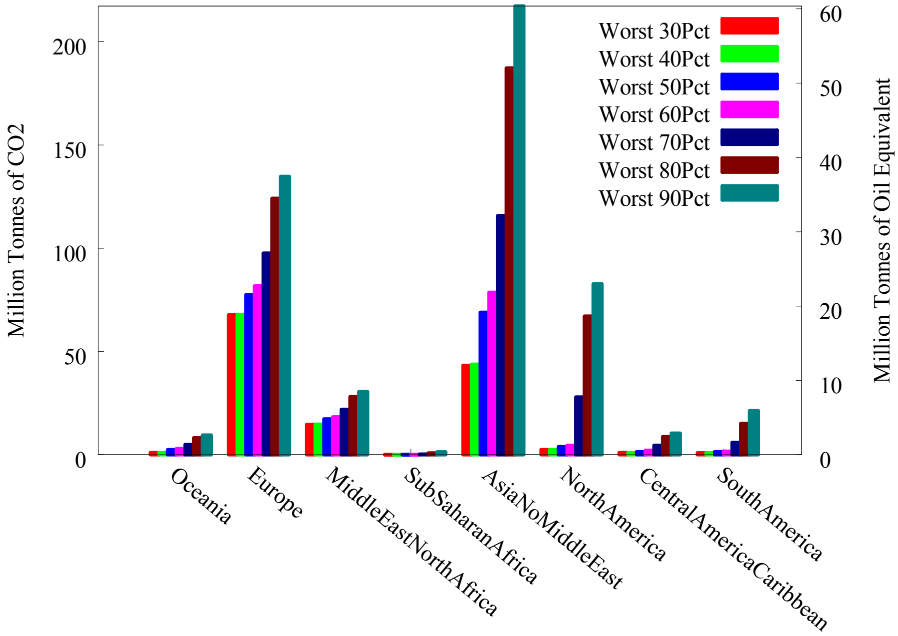

Figure 6 Regional distribution of global carbon savings from Figure 5 for year 2000