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Food Security and Fossil Energy Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003)

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The serious food crisis in 2007 has reinstated the issue of food security. In particular, it evokes an old set of questions associated with the sustainability of an adequate food supply: are we facing a systemic shortage of arable land for food production? How serious is the oil dependence of food security in relation to peak oil (the point in time when the maximum rate of global oil extraction is reached)? To answer these questions one has to study the role of technical inputs in agricultural production, especially those inputs generated from fossil energy (how much fossil energy is used? for which inputs? in relation to which tasks?). This paper provides a synchronic comparison—e.g., comparing the use of technical inputs in 21 countries belonging to different typologies, at a given point in time—and a diachronic comparison, e.g., comparing the use of technical inputs in the same sample of 21 countries, over a time window of 12 years (1991–2003). The results confirm the conclusions of previous studies and include the following: (i) current pattern of inputs use reflects the existence of different typologies of constraints in different typologies of countries. Wealthier countries must have a very high productivity of labor, whereas poor and crowded countries must have a very high productivity of land. Different technical inputs are used for different purposes: irrigation and fertilizers are used to boost yield per hectare; machinery and infrastructures to boost the productivity of labor; and (ii) when looking at the changes over the period of 12 years we see a constant and worrisome trend. The pattern of energy use in agriculture associated with the paradigm of industrial agriculture (High External Input Agriculture) has been simply amplified, by doing more of the same, with only minor adjustments in special countries. For those looking for a major transition toward a different pattern of production more focused on rural development, ecological compatibility and quality food, this is a reason for concern.

Keywords Fossil energy in agriculture, international comparison, energy output-input, demographic pressure, bio-economic pressure, energy analysis of food production, agricultural development

I. INTRODUCTION

In the five years previous to mid 2008 the prices of basic food commodities doubled or tripled. For instance, the cereals FAO price index went up from 95 in 2002 to 167 in 2007 (FAO, 2009). This generated a serious food crisis in 2007, which was experienced worldwide (both in developed and developing world) and primed food riots in many cities of developing countries (Krugman, 2008). This food crisis can be explained by a combination of the following factors: (i) increase in food demand due to world population growth; (ii) changes in dietary habits, with an increase in the consumption of animal products, which entail a double conversion of grains used to feed animals (Pingali, 2006); (iii) the occurrence of unfortunate events (such as a couple of poor years of production); and (iv) the increasing demand of grains for agro-biofuels (IMF, 2007; The Guardian, 2008; World Bank, 2008; Giampietro and Mayumi, 2009). The food crisis was harder in developing countries, where food's share in household spending is higher (IMF, 2007). Are we in the presence of a systemic change in the existing balance between demand and supply? In the affirmative, this would imply that the issue of food security, interpreted as the ability of producing enough food supply over a limited amount of available land—which is shrinking with demographic growth—will get more and more relevant at the world level.

In relation to this point, Ramonet (2009) reported that in the last years more than 8 million hectares of agricultural land have already been purchased worldwide by countries with a limited endowment of arable land per capita such as South Korea, China, Saudi Arabia, and Japan. These figures change according to the source. GRAIN (2008) called this process "land grabbing" and stated that to date more than 40 million acres have changed hands or were under negotiation—20 million of which were in Africa alone, with the side effect of reducing the number of small scale farmers and adding more pressure to water resources. Williams (2009), reporting on an UN event to try to prevent this trend in Africa, quoted David Hallam, deputy director of the trade and markets division at the UN's Food and Agriculture Organization (FAO) saying that "in the worst cases it's fair to say we are looking at neo-colonialism."

When dealing with the issue of food security and sustainability of agriculture, it is essential to focus on the constraint that the requirement of land, soil, water and other natural resources entails on the possibility of generating an adequate supply of food (Pimentel and Giampietro, 1994a). In fact, the severity of this constraint determines the amount of technical inputs that have to be used in agricultural production (or that should be used to get a certain output), which in turn affect the ecological impact of this production. Therefore, it is important to visualize the big picture of existing trends of technical progress in agriculture at the world level, in order to be able to contextualize the discussion of alternative techniques of agricultural production. When talking of the use of technical inputs in agriculture, it is well known that the revolution in the yields achieved in the last century can only be explained by the massive injections of fossil energy associated with modern techniques of agricultural production (Cottrell, 1955; Gever *et al.*, 1991; Leach, 1976; Odum, 1971; Pimentel and Pimentel, 1979; Smil, 1988, 1991, 2001; Steinhart and Steinhart, 1974). The success of this solution has been extraordinary: "In the past century, the world population has tripled from 2 billion at the beginning of the twentieth century to more than 6 billion at present. It is most impressive to say that the increase in the productivity of agriculture was able to meet the increase the demand for food by this increased population, at the same time that land per capita was proportionally shrinking. Moreover, agriculture did not only meet the growing food demand due to population growth, but it also succeeded to match the demand of food of more people consuming much more per capita. In fact, at present, the grain consumption per capita in developed countries is around 700 kg of grain per year with peaks up to 1,000 kg per year—when including the indirect consumption in the food system for animal production, beer production, and other industrial food products" (Giampietro and Mayumi, 2009). But this extraordinary success implies a risk, an increasing dependence of food security on fossil energy: "the survival of peasants in the rice fields of Hunan or Guadong—with their timeless clod-breaking hoes, docile buffaloes, and rice-cutting sickles—is now much more dependent on fossil fuels and modern chemical syntheses than the physical well-being of American city dwellers sustained by Iowa and Nebraska farmers cultivating sprawling grain fields with giant tractors. These farmers inject ammonia into soil to maximize operating profits and to grow enough feed for extraordinarily meaty diets; but half of all peasants in Southern China are alive because of the urea cast or ladled onto tiny fields—and very few of their children could be born and survive without spreading more of it in the years and decades ahead." (Smil, 1991, p. 593).

For this reason analyzing the dependence of food production on fossil energy has become a very important topic (Stout, 1991, 1992; Pimentel and Giampietro, 1994b; Giampietro, 2002; Pimentel and Pimentel, 1996; Smil, 1988, 1991, 2001).

Ten years ago, in another special issue of Critical Review in Plant Science dedicated to the sustainability of agriculture (Paoletti *et al.*, 1999), one of the papers was dedicated to an international comparison of the use of fossil energy in agriculture (Giampietro *et al.*, 1999). The goal was to study the different mixes of technical inputs used in different typologies of countries, over a significant sample of world countries. In this paper, we repeat, 10 years after, the same type of analysis with the goal of studying the evolution of the pattern of use of technical inputs in different typologies of countries. What happened in relation to this issue in the last ten years? Are we reducing the dependence of our food security on oil? These questions are extremely relevant since the era of cheap energy seems to be over and for good. The chosen sample includes countries at different levels of density of population (net exporters vs. net importers of food) and at different levels of economic development (developed vs. developing countries). The comparison over the chosen sample of countries refers to the years 1991 and 2003.

Looking at the future, peak oil could imply a possible reduction in the current heavy use of fossil energy inputs to agriculture. This reduction may very well be accompanied by an increase in labour inputs and a reduction of transport. This combination of changes could eventually lead to food production being devoted primarily to local consumption. This scenario seen by some authors as almost unavoidable—"Fossil fuel depletion almost ensures that this *will* happen" (Heinberg, 2007)—will represent a disaster for the growing mass of urban poor in many developing countries. To this regard, it should be noted that in 2007 more than 50% of human population was urban (UNFPA, 2008). This explains why, a better understanding of the link between the use of the different technical inputs and food production is essential for discussing future scenarios of food security. In particular, in order to develop alternative methods of production, it is important to compare the use of fossil energy (how much fossil energy? for which inputs? in relation to which tasks?) in the agricultural sector of different countries.

II. MATERIALS AND METHODS

A. The Sample

The selected sample is the same as in the previous CRPS paper of 1999, it includes 21 countries representing America, Europe, Asia, Africa and Australia. The chosen sample of countries covers different combinations of economic development (measured by GDP) and population density (measured by availability of arable land per capita).

- *Developed countries:* United States, Canada, and Australia (important food exporters with low population density), France (net food exporter within EU), the Netherlands, Italy, Germany, Spain, United Kingdom and Japan (net food importers).
- *Countries with an intermediate GDP:* Argentina (with abundant arable land), Mexico, and Costa Rica
- *Countries with a low GDP:* P.R. China, Bangladesh, India, and Egypt (all with little arable land per capita); Zimbabwe (net food exporter), Uganda, Burundi, Ghana.

B. The Theoretical Framework of the Analysis

The overall value of the output/input energy ratio of agricultural production, refers to two distinct typologies of energy flows: (A) the energy output, which is food energy produced in the crops; and (B) the energy input, which is the fossil energy embodied in the technical inputs used in agricultural production. These two flows are not directly related to each other in terms of their relative value to society. When analyzing the energetic efficiency of agricultural production we face a paradox (Giampietro *et al.*, 1999): "In the last decades technical development in agriculture has led to a reduced efficiency of energy use, when assessed by the output/input energy ratio in agricultural production (Pimentel and Pimentel, 1979; Pimentel *et al.* 1990) together with a diminished use of biodiversity in food production (Altieri *et al.*, 1987; Wilson, 1988)." To explain this paradox it is important to understand that beside the energetic efficiency of the agronomic production there are a lot of other relevant criteria of performance determined by the strong conditioning that the socioeconomic context imposes on the technical choices made at the farming system level (Giampietro *et al.*, 1994; Giampietro, 1997a, 1997b, 2003; Conforti and Giampietro, 1997). In particular explaining the evolution in the pattern of use of technical inputs in agricultural systems requires establishing a relation between

1. *changes taking place in the socio-economic context of the farm.* For this task we use in this analysis two indicators: demographic and bio-economic pressure; and
2. *changes taking place within the farm.* For this task we check in this analysis the changes taking place in the pattern of use of technical inputs—the mix of irrigation, fertilizer, pesticides, and machinery.

The basic rationale behind this analysis is that technical progress of agriculture has been driven by two objectives (Hayami and Ruttan, 1985; Giampietro, 1997b): (1) boost the productivity of labor in the agricultural sector; and (2) boost the productivity of land in production. Therefore, technical progress (coupled to economic growth) has implied a continuous increase in the injection of technical inputs into the process of agricultural production in order to increase the net supply of: (i) food per hectare (in response to the growing Demographic Pressure); and (ii) food per hour of labor in the agricultural sector (in response to the growing Bio-Economic Pressure).

As explained by Giampietro and Mayumi (2009) "The priority given to these two objectives, under the alleged label of "technological progress in agriculture," has been driven by two crucial transformations that took place in developed societies in previous decades:

1. A dramatic socioeconomic re-adjustment of the profile of investment of human time, labor and capital over the different economic sectors in industrial and post-industrial societies. This transformation required the progressive elimination of farmers to free labor for the work force in other economic sectors, initially the industrial sector and later the service sector;
2. The demographic explosion that took place, first in the developed world and later everywhere, linked to the phenomenon characterized as 'globalization of the economy'. This explosion did, and still does require boosting the yields on land in production due to the progressive reduction of the available arable land per capita."

To study the different effects of these two pressures on the technical development of agriculture in the countries included in the sample in this study we assume the following relations:

(i) the performance in terms of "land productivity"—the level of crop production per hectare (MJ/ha)—is correlated to differences in "demographic pressure." An increase in demographic pressure is defined as the reduction in available cropland per capita, associated with population growth. An increase in Demographic Pressure implies the need to boost the yields per hectare, to remain self-sufficient in food production;

(ii) the performance in terms of "labor productivity"—the level of crop production per hour of work allocated to agriculture (MJ/hour)—is correlated to differences in "bio-economic pressure."

Increase in bio-economic pressure (BEP) is defined as the reduction of the fraction of farmers in the work force, associated with economic growth. An increase in BEP makes it necessary to produce more crops per hour of work in agriculture, to remain self-sufficient in food production. The main factor determining the increase in BEP is economic growth in the economy, rather than any "biological" factor. Using the jargon used in conventional development economics, the process of declining active population in agriculture is explained as follows. Labor productivity goes up in agriculture because of technical improvement (nothing is said about energy input), while production cannot increase at the same pace of productivity because of low income-elasticity of demand for agricultural products as a whole (Engel's Law). Therefore, economic growth implies that agriculture tends to expel active population.

This assumption of an existing relation between: (i) agricultural land productivity and Demographic Pressure (DP); and (ii) agricultural labor productivity and Bio-Economic Pressure ; was confirmed by the empirical analysis discussed in two previous papers (Giampietro, 1997b; Conforti and Giampietro, 1997).

In this paper we characterize changes in relation to these concepts as follows:

#1. Demographic Pressure (DP) and Bio-Economic Pressure (BEP)—seen as drivers of technical progress in agriculture

Demographic Pressure—to quantify the demographic pressure on agricultural production we calculate the level of agricultural productivity imposed by demographic pressure. This is defined as the productivity of land (yield of food energy per hectare) that would be needed to obtain a situation of complete food self-sufficiency in society (Giampietro, 1997b; Giampietro *et al*., 1999). This threshold level can be calculated from:

- The aggregate requirement of food in society (considering the food system under analysis as closed), which is determined by the population size of society, food consumption pattern, and post-harvest losses. This information is available by consulting FAO Food Balance Sheet (total consumption of the population). In this study we consider the energetic value of plant crops (consumed directly and indirectly), to account for differences in the quality of the diet, determined by the amount of animal products, requiring a double conversion of plant calories into animal product calories—for more see Giampietro (1997b).
- The land available for food production, which depends on availability of arable land, characteristics of this arable land, and alternative land uses (dependent on population size and technological development). This information is available from FAO statistics (arable land and permanent crops). High demographic pressure in society will invariably favor farming techniques and crop mixes that yield a high food production per unit of area (Boserup, 1981; Hayami and Ruttan, 1985). This implies that the higher is the demographic pressure —proxy: population divided by colonized land—the higher can be expected to be the productivity of land—proxy: the food energy yields of cultivated crops.

Bio-Economic Pressure in agriculture—the bio-economic pressure determined by economic growth can be described as the need of reaching high level of labor productivity in specialized compartments of the economy, which are in charge of producing the supply of critical input consumed by society (Giampietro and Mayumi, 2000, 2009). In relation to food security, the bio-economic pressure indicates the level of productivity of labor, which should be achieved per hour of labor in agriculture, to obtain a situation of complete food self-sufficiency in society. For example, in 1999 the entire amount of food consumed per capita in a year by a U.S. citizen (the United States is among the countries with the highest consumption of food items per capita) was produced using only 17 hours of work in the U.S. agricultural sector (Giampietro, 2002). In general, quantitative indicators of Bio-Economic Pressure correlate well with all the other indicators of development such as Gross Domestic Product or commercial energy consumption per capita (Pastore *et al.*, 2000).

In this paper, we define Bio-Economic Pressure in Agriculture as the level of agricultural labor productivity (yield of food energy per hour of labor in the agricultural sector) that would be required to produce the food consumed in a society. In this calculation we consider the same overall energetic requirement of food calculated for determining the demographic pressure. That is, we consider the society's food system as closed. Then, we divide the aggregate requirement of primary food energy of the whole society in a year by the labor time available in a year in the agricultural sector. The latter depends on the size of the labor force, the unemployment rate, the fraction of the labor force absorbed by the nonagricultural sectors, and the average work load (Giampietro, 1997b). A high Bio-Economic Pressure in society favors farming techniques and crop mixes that yield a high food production per hour of work (Hayami and Ruttan, 1985; Giampietro, 1997b). That is, the higher is the Bio-Economic Pressure in agriculture—proxy: total primary food energy consumed by the society (total food consumption) per hour of work in the agricultural sector (numbers of active workers in agriculture × 2000 hours/year)—the higher can be expected to be the productivity of labor of farmers—proxy: the amount of food energy produced per hour of work in agriculture.

As a matter of fact, imports and exports make it possible for modern societies to have a certain level of independence between: (a) the level of internal consumption of food both per hour of work in agriculture and per hectare of land in production in agriculture; and (b) the level of internal production of food both per hour of work in agriculture and per hectare of land in production in agriculture. However, as proved by the empirical analysis, these two distinct types of pressure play an important role in shaping the use of technical inputs across world countries.

#2. The use of technical inputs in relation to these two different pressures: (i) irrigation and fertilizers are required to deal with the demographic pressure; whereas (ii) machinery is required to deal with the Bio-Economic Pressure.

Previous studies on the use of technical inputs in agriculture (Giampietro 1997b; 2002; Conforti and Giampietro, 1997; Giampietro *et al.*, 1999) provided the following explanations in relation to the mix of inputs used in different typologies of agricultural production:

* Irrigation and fertilizers are used more in crowded countries, independently of the level of economic growth, since they respond to the intensity of the demographic pressure—they boost the production per hectare of land.

* Machinery is used, but in special niches, only in developed countries, independently of the level of demographic pressure, since it responds to the intensity of the Bio-Economic Pressure—they boost the production per hour of labor.

In this study we will double-check these assumptions not only by providing a synchronic comparison, e.g., comparing the use of inputs of 21 countries belonging to different typologies at a given point in time. We will also provide a diachronic comparison, e.g., the comparison over the same sample of 21 countries performed at two points in time 1991 and 2003, that is, over a time window of 12 years.

C. Data Source and Conversion Factors

The quantitative assessments given in this study are based on:

1. *The Data-Set Taken From FAO Agricultural Statistics*

Databases for world agricultural production are available at FAO web site (http://www.fao.org/corp/statistics). We selected data referring to 1991 and 2003. This database covers different aspects of agricultural production: (1) means of production, e.g., various technological inputs used in production (excluding data on pesticide use), (2) food balance sheets—accounting of production, imports, exports and end uses of various products, as well as composition of diet and energetic value of each item, per each social system considered; (3) data on agricultural production, and (4) data on population and land use. Data on pesticides have been estimated using data from literature. Assessments of pesticide consumption have been re-arranged starting from the estimates of Pimentel (1997) to fit FAO system of aggregation.

The data used in this study are reported in Table 1.

2. *The Set of Energy Conversion Factors Taken From an Overview of the Available Data in the Specialized Literature*

Energy conversion factors tend to apply generalized values, but at the same time to reflect peculiar characteristics of various socio-economic contexts in which agricultural production occurs (e.g., reflecting the system of aggregation provided by FAO statistics).

The conversion factors used to assess the amount of embodied fossil energy are slightly different from those used in the original study of Giampietro *et al.*, 1999, since some data have been updated. For this reason, the original data set used in the CRPS paper of Giampietro *et al.* (1999) has been recalculated using this set of conversion factors to obtain a better comparability of the two assessments presented in this paper referring to 1991 and 2003.

TABLE 1
Relevant characteristics of selected countries.

	Technical Inputs																					
	Gross Foot Consumption (PJ/Year)		Gross Food Production (PJ/Year)		Land in Production (MHa)		Work in Production (MHours)		Irrigation (1000sHa)		Harversters-Threshers		Tractors		Nitrogenous Fert. Consumption Tonnes		Phosphate Fertilizers Tonnes		Potash Fertilizers Tonnes		Pesticides Tonnes	
	91	2003	91	2003	91	2003	91	2003	91	2002	91	2003	91	2003	91	2002	91	2002	91	2002	92	2000
Argentina	175	211	407	660	27	29	2962	2916	1560	1561	48800	50000	274034	299620	95700	432628	54500	283300	17100	23598	—	—
Australia	125	210	318	615	46	48	924	878	4	4	56600	56500	316000	315000	462300	972300	680200	1077290	142100	230000	119654	—
Bangladesh	376	523	325	455	9	8	70414	78932	3027	4597	0	0	5250	5530	705600	1049900	216600	222300	82200	151400	2906	6340
Burundi	20	20	20	19	1	3	5616	6468	72	74	2	2	165	170	1000	852	1000	711	100	976	186	218
Canada	347	492	689	683	52	52	966	724	720	785	152114	115800	734149	732600	1253287	1629763	592300	637910	327497	346082	58936	—
China	5844	6481	5586	6218	131	155	993050	1021146	48384	54937	43996	362200	795713	995421	19970500	25430147	7284300	9924054	2404300	4250465	208	37
Costa Rica	16	23	16	22	1	1	618	652	78	108	1180	1190	6500	7000	62400	52068	16000	33743	38000	65751	—	40120
Egypt	360	501	224	320	3	3	15340	17070	2643	3400	2260	2325	59000	89700	775000	1068923	150000	142179	38400	57701	10954	—
France	487	542	890	836	19	20	2606	1562	2100	2600	122300	91000	1410000	1264000	2569000	2279000	1255000	729000	1741000	960000	85249	97490
Germany	581	706	639	688	12	12	3044	1762	482	485	141200	135000	1500000	944000	1720000	1787654	519000	327000	729658	479673	55415	57788
Ghana	75	122	69	112	4	6	8670	11762	9	11	130	19	4050	3600	7000	14170	200	8590	800	8270	—	164
India	3150	4013	3095	3790	169	170	466048	547030	47430	57198	3000	4200	1063012	2528122	8046272	10470810	3321213	4004779	1360600	1646993	141539	91487
Italy	182	425	171	302	12	11	4024	2316	2710	2750	47715	37500	1455811	1680000	906720	785314	661970	372026	418000	275302	170169	150450
Japan	736	697	263	239	5	5	8878	4618	2825	2607	1169000	1042000	1966000	2028000	576000	463000	696000	482000	480000	339000	—	—
Mexico	538	797	432	563	26	27	17106	16968	5800	6320	19000	22500	317313	324890	1155200	1176400	379900	349900	84300	185600	—	—
Netherlands	152	198	103	115	1	1	616	454	557	565	5560	5600	182000	149500	391759	284000	75000	52000	94000	66000	—	—
Spain	346	513	338	409	20	19	3656	2330	3388	3780	48821	50454	755743	943653	862156	802500	501655	601300	381382	488300	31839	35700
Uganda	83	123	81	115	7	7	15238	7312000	9	9	15	15	4600	4700	500	4330	300	2698	400	2278	144	
UK	369	428	355	350	7	6	1200	1002	165	170	48000	47000	500000	500000	1365000	1142000	365000	283000	441000	376000	59448	63093
US	3146	3838	3769	4764	188	176	7156	5696	20900	22500	663000	662000	4541725	4760000	10383900	10878330	3826400	3874960	4573700	4545159	408686	—
Zimbabwe	32	39	34	29	3	1	6546	7154	100	117	833	800	18000	240	89822	60000	43200	30000	31100	20000	5222	—

Source: Data from FAOSTAT and WRI.

(1) Machinery—to assess energy equivalent of machinery from FAO statistics we adopted basic conversion factors suggested by Stout (1991), since they refer directly to FAO system of accounting. A standard weight of 15 Metric Tons (MT) per piece (both for Tractors and for Harvester and Thresher) for the United States, Canada, and Australia; a common value of 8 MT for pieces in Argentina and Europe; a common value of 6 MT for pieces in Africa and Asia. To the resulting machinery weight Stout suggests an energy equivalent of 143.2 GJ/Metric Ton of machinery. This value (which includes maintenance, spare parts and repairs) is quite high, but it has to be discounted for the life span of machinery. It is the selection of the useful life, which will define, in ultimate analysis, the energy equivalent of a metric ton of machinery. Looking at other assessments, made following a different logic, it is possible to find in literature values between 60 MJ/kg for H&T and 80 MJ/kg for tractors, but only for the making of the machinery. The range of 100–200 MJ/kg found in Leach analysis (Leach, 1976) includes also the depreciation and repair. Pimentel and Pimentel (1996) suggest an "overhead" of 25–30% for maintenance and repairing to be added to the energy cost of making. In general a 10-year life-span is applied to these assessments. The original value of 143.2 GJ/Metric Ton of machinery suggested by Stout can be imagined for a longer life-span than 10 years (the higher the cost of maintenance and spare parts the larger should be the life span). Depending on different types of machinery the range can be 12–15 years. Therefore, in this assessment a flat discount of 14 years has been applied to the tons of machinery, providing an energy equivalent of 10 GJ/MT/year.

(2) Oil consumption per piece of machinery—conversion factors from Stout (1991). Again, these factors refer directly to data found in FAO statistics. The estimates of consumption of fuel per piece are the following: 5 MT/year for the United States, Canada, and Australia; 3.5 MT/year for Argentina and Europe; 3 MT/year for Africa and Asia. The energy equivalent suggested by Stout is quite low (42.2 GJ/MT of fuel – typical for gasoline, without considering the cost of making and handling it). A quite conservative value of 45 GJ/MT as average fossil energy cost of "fuel" has been adopted.

(3) Fertilizers—conversion factors from Hesel (1992), within the Encyclopedia edited by Stout (1992). These assessments include also the packaging, transportation and handling of the fertilizers to the shop. Values are:

- For Nitrogen, 78.06 MJ/kg—this is higher than the average value of 60–63 MJ/kg for production (Smil, 1987; Pimentel and Pimentel, 1996) and lower than the value estimated for production of Nitrogen in inefficient plants powered by coal (e.g., in China), that can reach the 85 MJ/kg reported by Smil (1987).
- For Phosphorous, 17.39 MJ/kg—this is higher than the standard value of 12.5 MJ/kg reported for the process of production (Pimentel and Pimentel, 1996). But still in the range reported by various authors: 10–25 MJ/kg by Smil (1987), 12.5–26.0 MJ/kg by Pimentel and Pimentel (1996). The packaging and the handling can explain the movement toward the upper value in the range.
- For Potassium, 13,69 MJ/kg—also in this case the value is quite higher than the standard value of 6.7 MJ/kg reported for production. Ranges are 4–9 MJ/kg given by Smil (1987) and 6.5–10.5 MJ/kg given by Pimentel and Pimentel (1996). Clearly, the energy related to the packaging and handling, in this case influences in a more evident way the increase in the overall cost per kg.

(4)Irrigation—conversion factors suggested by Stout (1991) are 8.37 GJ/ha/year for Argentina, Europe, Canada, the United States, and Asia; and 9.62 GJ/ha/year for Africa and Australia. These values refer to full fossil energy based irrigation. However, when looking at FAO statistics on irrigation one can assume that only a 50% of it is machine irrigated. So that this conversion factor has been applied only to 50% of the area indicated as irrigated (but in Australia).

(5) Pesticides—a flat value of 420 MJ/kg has been used for both developed and developing countries. This includes packaging and handling (Hesel, 1992). Values in literature vary between 293 MJ/kg for low quality pesticides in developing countries to 400 MJ/kg in developed countries (without including packaging and handling).

(6) Other energy inputs—at the agricultural level there are other technical inputs which are required for primary production. For example, infrastructures (commercial buildings, fences), electricity for on farm operations (e.g., drying crops), energy for heating, embodied energy in vehicles and fuels used for transportation. For this reason a flat 5% of the sum of previous energy inputs has been adopted in this analysis. This has been applied only to agricultural production in developed countries.

III. THE RESULTS OF THE STUDY

A. The effect of changes in Demographic Pressure and Bio-Economic Pressure

In relation to the 21 countries included in the sample we report in Table 2:

(i) the actual *land productivity* (density of the internal supply of food energy per hectare) and the threshold of the density of production per hectare that would be required to be self-sufficient according to the *demographic pressure*;

(ii) the actual *labor productivity* (intensity of the internal supply of food energy per hour of labor) and the threshold of the density of production per hour of labor that would be required to be self-sufficient according to the *Bio-Economic Pressure*.

The pattern of correlation of the two values of: (i) actual density of food energy supply per hectare of arable land in

TABLE 2
A comparison between levels of productivity per ha and per hour: (i) actually achieved, and (ii) needed for self-sufficiency

	Land Productivity (actual Supply) (GJ/Ha)		Demographic Pressure (needed for self-sufficiency) (GJ/Ha)		Labor Poductivity (actual Supply) (MJ/hr)		Bio-Economic Pressure (needed for self-sufficiency) (MJ/hr)	
Country	1991	2003	1991	2003	1991	2003	1991	2003
Argentina	14,8	22,8	6,4	7,3	137,3	226,3	59,1	72,5
Australia	6,9	12,8	2,7	4,4	344,2	700,1	135,3	238,8
Bangladesh	35,6	54,0	41,1	62,1	4,6	5,8	5,3	6,6
Burundi	15,1	14,1	15,4	14,8	3,5	2,9	3,5	3,1
Canada	13,3	13,1	6,7	9,4	712,8	943,2	359,4	679,3
China	42,5	40,2	44,5	41,9	5,6	6,1	5,9	6,3
Costa Rica	31,9	41,6	30,5	44,7	26,6	33,5	25,4	36,0
Egypt	84,8	93,3	136,1	146,3	14,6	18,7	23,5	29,4
France	46,3	42,7	25,3	27,7	341,4	535,3	186,7	346,9
Germany	54,1	57,1	49,2	58,6	209,9	390,5	190,9	400,6
Ghana	16,0	17,6	17,3	19,2	8,0	9,6	8,6	10,4
India	18,3	22,3	18,6	23,6	6,6	6,9	6,8	7,3
Italy	14,4	28,3	15,3	39,8	42,5	130,6	45,1	183,7
Japan	50,5	50,4	141,4	147,1	29,6	51,7	82,9	150,9
Mexico	16,6	20,6	20,7	29,2	25,3	33,2	31,5	47,0
Netherlands	112,5	121,9	166,5	210,3	166,4	253,4	246,2	437,2
Spain	16,8	21,9	17,2	27,4	92,4	175,7	94,6	220,0
Uganda	11,8	15,7	12,0	16,7	5,3	5,9	5,4	6,3
UK	53,6	61,3	55,7	75,0	296,1	349,3	307,8	427,4
US	20,1	27,1	16,8	21,9	526,7	836,4	439,6	673,8
Zimbabwe	11,2	8,7	10,6	11,5	5,2	4,1	4,9	5,4

production; and (ii) needed density of food energy supply per hectare of arable land to be self-sufficient is illustrated in Figure 1. The graph shows that the original correlation found in 1991, remained throughout the time window—the movement of the values over time has been on a diagonal to arrive to the points recorded in 2003. This confirms the findings of previous studies (Giampietro, 1997b; Conforti and Giampietro, 1997). That is, the countries that have high demographic pressure (DP) tend to have a high production of food energy per hectare. The group of countries that have the highest demographic and land productivity are the Netherlands, Egypt and Japan. Another cluster includes the United Kingdom, Germany and Bangladesh. For a cluster analysis over this type of comparison see Conforti and Giampietro (1997).

In other words, current technological performance in agriculture in terms of yield per hectare is affected by existing demographic pressure.

The same analysis, referred to the intensity of food production (actual versus needed) per hour of labor is illustrated in Figure 2. The two values of: (i) actual intensity of food energy supply per hour of work in agriculture in production; and (ii) needed intensity of food energy supply per hour of work in agriculture to be self-sufficient, originally correlated over the sample in 1991, keep the same pattern in 2003. Also in this case the

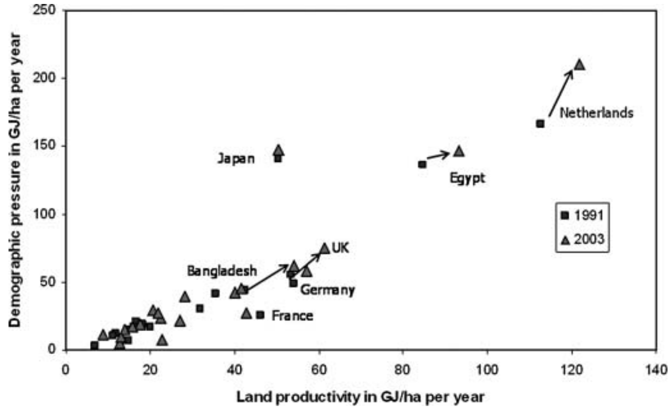

FIG. 1. Land productivity versus demographic pressure.

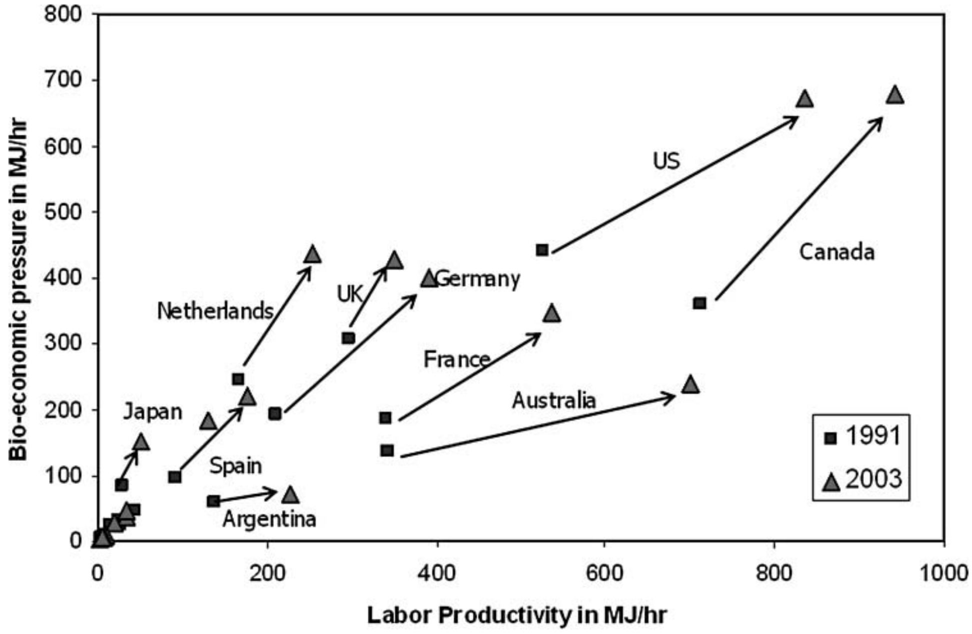

FIG. 2. Labor productivity versus bio-economic pressure.

movement of the values has been on a diagonal. That is, the countries that have a high Bio-Economic Pressure tend to have also a high production of food energy per hour of labor in their agricultural sector.

In this analysis we can observe three groups for developed countries, which all have increased their intensity of the flow of energy per hour over the given time window: (a) those that had the BEP already very high: USA by 53%, and Canada by 89%; (b) those that had medium high: Australia by 76%, France by 85%, Germany by 109%, UK by 53% and Netherlands by 77%; (c) those that had a BEP low in relation to the standard of developed countries: Spain, Japan, and Italy. All the other developing countries remained more or less stable in relation to the intensity of production per hour (as will be discussed later). Argentina is a special case, being a country which is an important food exporter with abundant land per capita. Hence, this analysis confirms that technological performance in agriculture in terms of actual labor productivity is definitely affected by changes in Bio-Economic Pressure (which reflects increasing levels of consumption), but this effect is more evident in developed countries.

What are the implications of this fact? The idea that the various countries included in the sample strive for self-sufficiency in food production is, of course, a simplification of reality. We all know that in a globalized world international trade plays a significant role in stabilizing equilibrium between the requirement and supply of food (Giampietro, 1997b). As a matter of fact, the majority of the countries included in this sample are net food importers (see Table 1). Still, it is important to observe that even those countries that heavily rely on food imports, e.g., Japan, because of their high demographic pressure tend to use in a more intensive way their land in order to produce as much as possible food on their own land.

In general terms we can say that the effect of demographic growth has implied that the arable land per capita has been decreasing over all the 21 countries, when considering the difference between 1991 and 2003. However, as illustrated in Figure 3, the overall decrease in arable land per capita does not coincide with an analogous reduction in arable land per farmer. In fact, a dramatic reduction of the number of farmers in the economy of modern societies, can offset the reduction of arable land per capita due to an increase in DP and imply an increase in arable land per farmers due to an increase in BEP.

For instance, looking at our data set the arable land per capita in 1991, this value is about the same for the United States (0.72 ha) and Argentina (0.83 ha) whereas the arable land and permanent crops per agricultural worker is much larger in the United States (52 ha) than in Argentina (18 ha). The same type of difference, determined by the difference in the fraction of farmers in the work force of the two countries, remained in 2003. The arable land per capita was still similar in the U.S. (0.59 ha) and for Argentina (0.75 ha) in 2003. Still, again, the amount of arable per farmer was much large in the U.S. (61 ha) than in Argentina (19 ha) due to the much smaller percentage of farmers in the labor force in the United States.

Similarly, densely populated European countries, such as Germany France, Italy and the UK, have limited amount of arable land per capita—in the range of 0.12–0.20 ha per capita. These values are comparable with the values of arable land

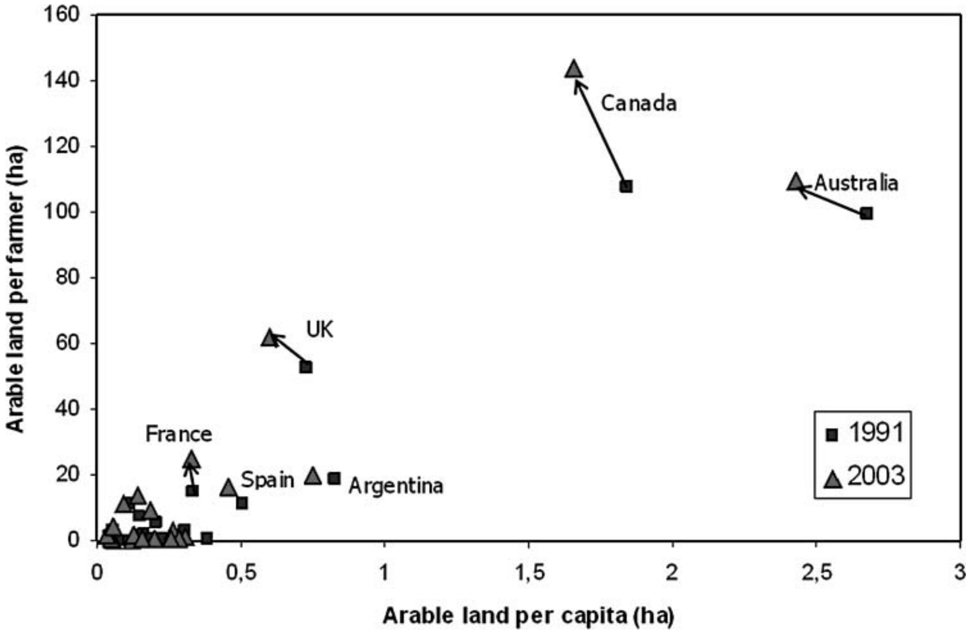

FIG. 3. Arable land per capita versus arable land per farmer.

available per capita in India or Burundi. However, the percentage of farmers in the work force of European countries (around 2% in 1991 and around 1.5% in 2003) is much smaller than the values found in developing countries (e.g., 49% in 1991 and 47% in 2003 for Burundi or 42% in 1991 and 38% in 2003 for China). This implies that, at the same level of DP, the amount of arable land per farmer is larger in countries having a higher level of BEP.

This last observation requires looking at another relation implied by the theoretical framework adopted in this study. The increase in Bio-Economic Pressure (the reduction of the fraction of farmers in the work force) is directly associated with the level of economic growth—the level of GDP—of a society. As illustrated in Figure 4 both the fraction of the work force in agriculture and the fraction of GDP from agriculture decrease dramatically for countries with high levels of GDP. No developed country has a percentage of work force in agriculture larger than 5%. The pattern is pretty robust over the considered time window.

B. Technological Inputs Dealing with Increase in Demographic Pressure (How to Boost Land Productivity with Irrigation and Fertilizers)

1. *Irrigation*

Irrigation is a costly way to augment the yield per hectare. Apart from scarcity of water (Postel, 1997), irrigation requires expensive fixed investments and large energy inputs for operation. For example, a corn crop producing 9,000 kg/ha requires about 7 million liters of water (Pimentel *et al.*, 2004). Irrigated corn in Nebraska requires three times more fossil energy than a rainfed corn crop in eastern Nebraska producing the same yield (Pimentel *et al.*, 2004). The relationship between land availability and the use of irrigation for the sample of selected countries is shown in Figure 5. It shows that the more a country is faced with land constraints, the more its agriculture relies on irrigation. Exceptions are Burundi, Ghana, Uganda, and Zimbabwe, which are located in the humid tropics or subtropical areas of Africa and have sufficient rainfall (we are referring to national averages).

When checking the relationship between changes in GDP per capita and changes in the use of irrigation over the period 1991 and 2003 we find (as illustrated in Figure 6) that increases in Bio-Economic Pressure associated with increases in GDP p.c. do not necessarily translate in an increase of irrigation (Giampietro, 1997b; Giampietro *et al.* 1999). This analysis confirms the point that the input of irrigation is applied to augment the yields per hectare, and that therefore it is not directly related to the need of increasing the productivity of farm labor.

2. *Nitrogen fertilizer*

The rise of N in fertilizer has increased worldwide of about 150% in many crops (Frink *et al.*, 1999). In addition to its growing use, the N fertilizer is the most 'expensive' technical input in terms of fossil energy. This is the reason why we are focusing on the use of the N fertilizer as the representative of the entire class of fertilizers.

The relationship between land availability and use of nitrogen fertilizer, shown in Figure 7, indicates that agriculture in countries with land shortage tends to use as much fertilizer as possible. Like for the input of irrigation we can say that—when considering the picture obtained at a large scale—the input fertilizer is applied to augment yield per hectare. That is, the use

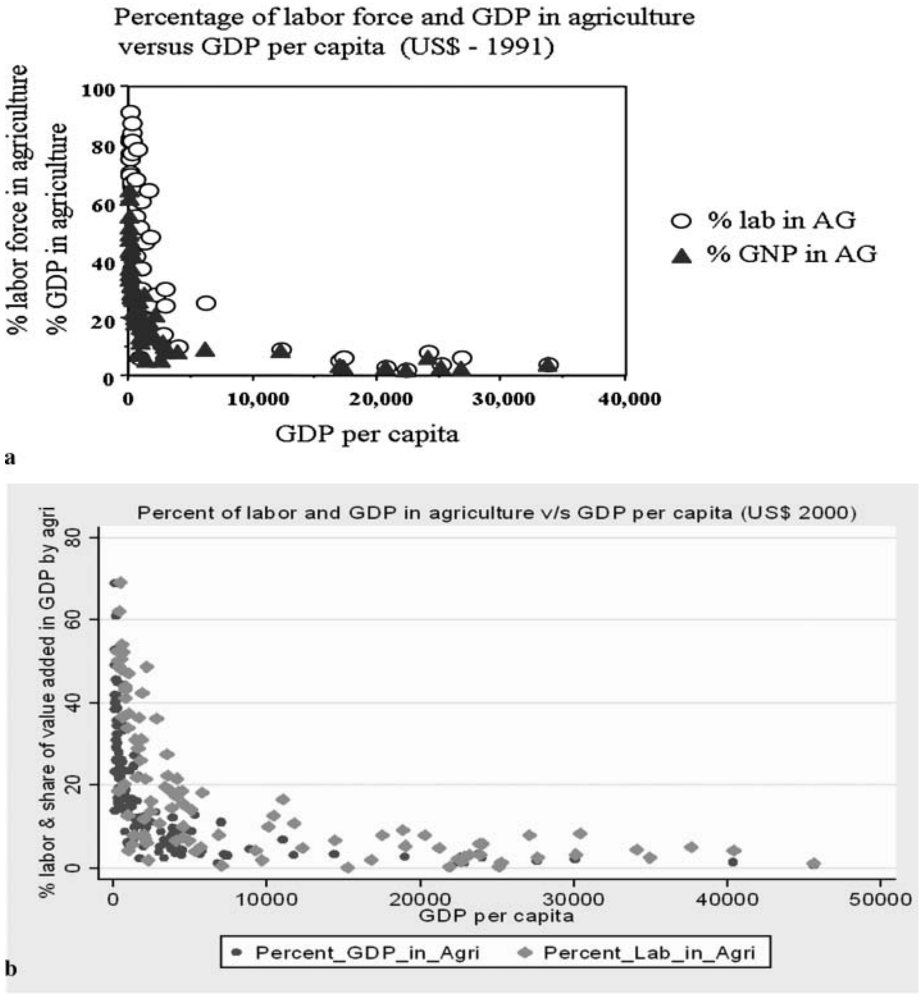

FIG. 4. Economic development and marginalization of the agricultural sector.

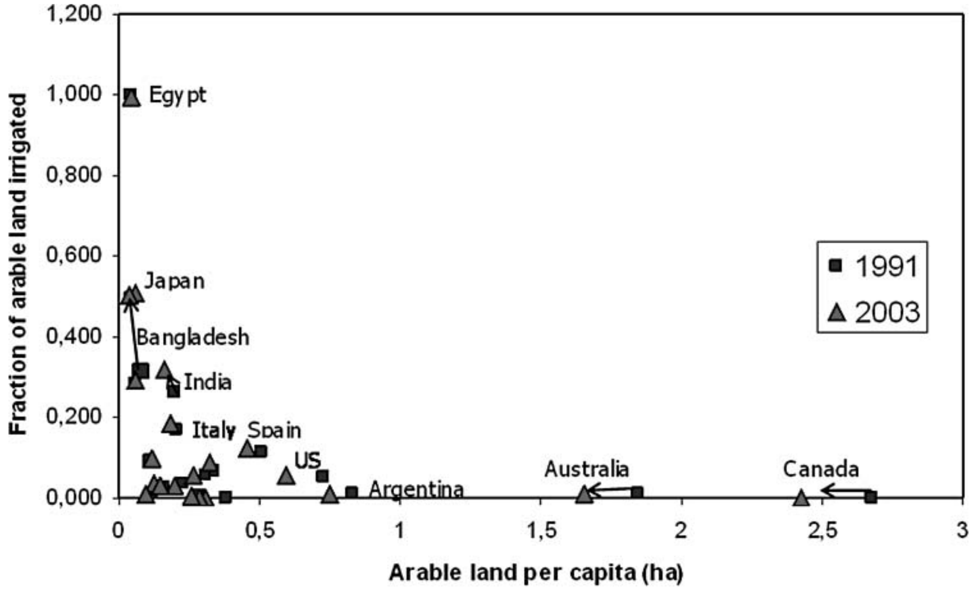

FIG. 5. Land availability versus use of irrigation.

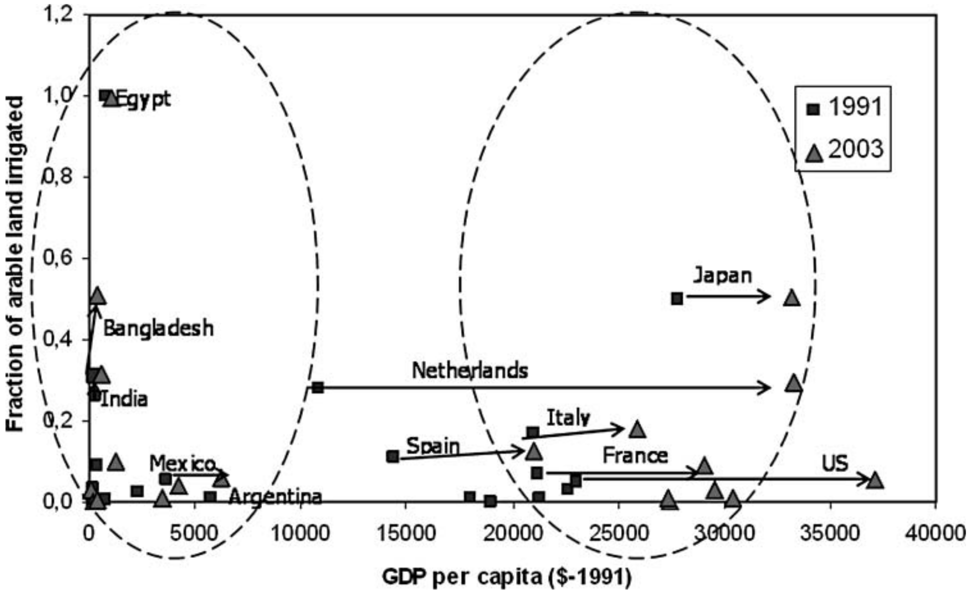

FIG. 6. GDP versus arable land irrigated.

of this input is not directly related to the need of increasing the productivity of farm labor.

When nitrogen use is put in relation with GDP per capita (Figure 8), we can see a clear division between developed and developing countries. Within each of these two groups, nitrogen use appears to be related to scarcity of arable land (according to the pattern observed in Figure 7). Changes related to changes in GDP (the differences between the year 1991 and 2003), shows that in some countries—notably The Netherlands reducing the consumption of 43%—the consumption of fertilizer has been adjusted, optimizing its use in relation to economic performance and environmental impact (reducing the leakage of P and N in the water table).

C. Technological Inputs Dealing with Increase in Bio-economic Pressure (How to Boost Labor Productivity with Machinery)

1. *Machinery*

The relationship between machinery per farmer and GDP per capita for the 21 selected countries is shown in Figure 9. The use of tractors does indeed appear to be related to the level of GDP, which in turn translates into the need to achieve high labor productivity for farmers. Although densely populated countries, such as Japan and some of the European countries with limited amount of arable land, make this relation nonlinear.

In this graph it is clear that tractors are used only by developed countries with the exception of special countries having the option of becoming grain exporters (Argentina in our sample).

A crucial factor determining the use of tractors is land availability, which depends on the available land per farmer—this is to say on demographic pressure, economic development and land tenure. This relation is illustrated in Figure 10, which puts tractor use per farmer in relation to land availability per farmer.

From this graph one can see that agricultural sectors facing shortage of arable land are less likely to increase their use of machinery per farmer, especially in developing countries. By looking at the changes taking place in developed countries we can notice that the use of Tractors and Harvesters reflects the effects of high levels of Bio-Economic Pressure determining a tiny working force in agriculture.

D. Limited Substitutability of Natural Capital with Technological Inputs

Most of the countries of the world are now to some degree dependent on food imports. These imports come from cereal surpluses produced in only a few countries that have a relatively low population density and intensive agriculture. For instance, in the year 2003, the United States, Canada, Australia, and Argentina provided about 45% of net cereal export on the world market (FAO, 2005).

It is easy to guess that if the Demographic Pressure (DP) increases also in exporting countries, they will see their internal grain demand increase and their available arable land per capita decrease. Let us remind here that the value of DP is not only affected by population growth, but also by changes in the diet towards more meat consumption, as the ones reported by Pingali (2006) for Asia. This is so because in the calculation we also include feedstuffs for animals. Under these conditions the cereal grain surplus now exported on the international market may be seriously eroded. This will make even more important the challenge determined by the continuous increase in demographic pressure in those countries which are already importing food.

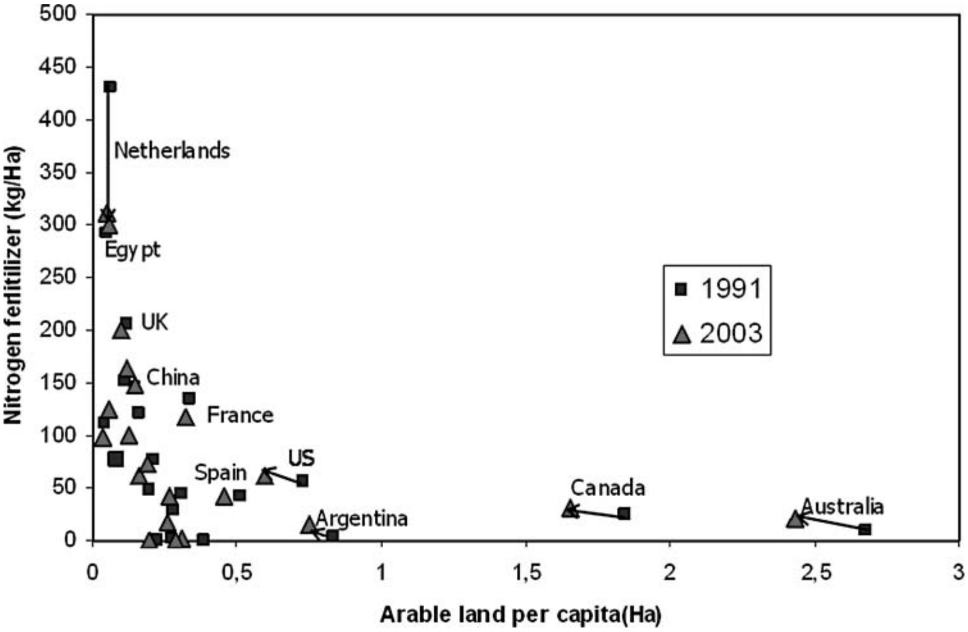

FIG. 7. Arable land versus nitrogen fertilize.

As discussed in the introduction many developing countries rely heavily on fossil energy, especially in form of fertilizers, to sustain their internal food supply. A future slow down of fossil energy consumption because of either a decline of oil supplies, increase in oil prices, or growing restrictions on fossil fuel use to limit its environmental impacts may very well generate a direct competition between fossil energy use in developed countries, to sustain a high standard of living, and that in developing countries, to provide an adequate food supply for survival (Pimentel and Giampietro, 1994b). The recent food crisis generated by large scale agro-biofuel production can be interpreted as a first example of this problem (Giampietro and Mayumi, 2009).

On the other hand, it is obvious that the ability of boosting labor productivity of farmers by using more machinery makes only sense in presence of the availability of a large amount of arable land per farmer. The relation between arable land per farmer and labor productivity is shown in Figure 11. This figure shows that at a given point in time, there is a clear relation between

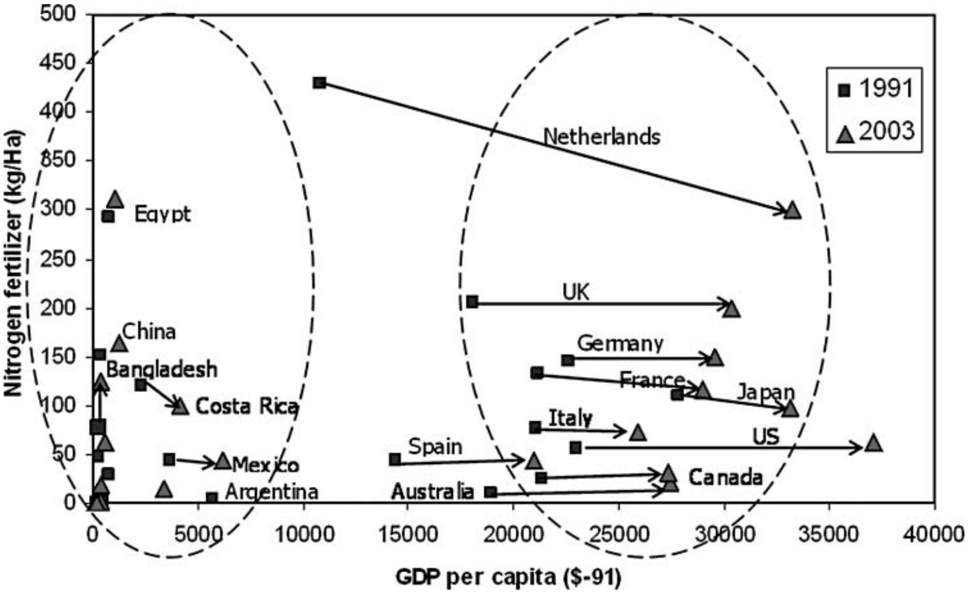

FIG. 8. GDP versus Nitrogen fertilizer.

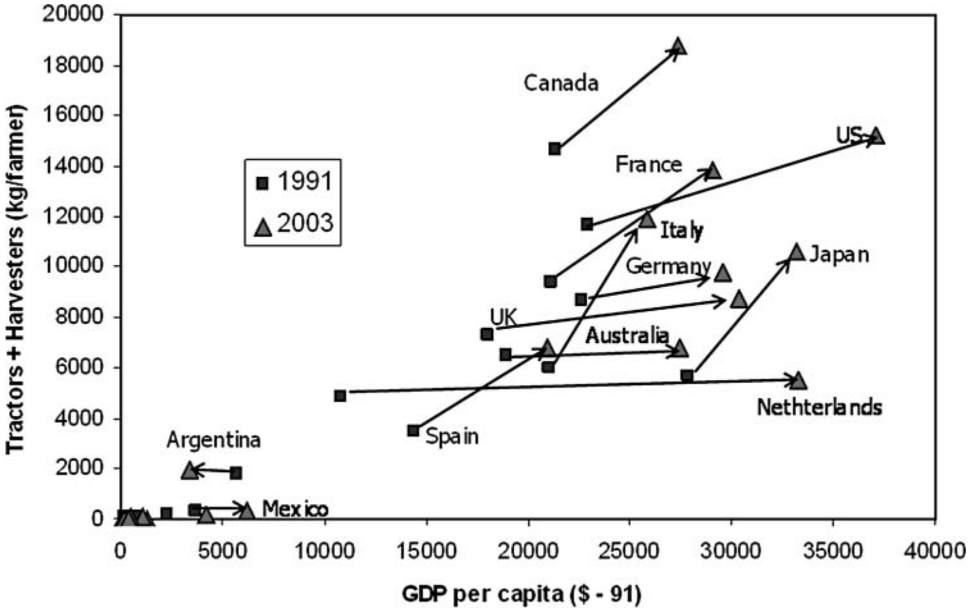

FIG. 9. GDP versus tractors-harvesters.

availability of arable land and labor productivity. This relation, however, can be established only by the use of an increasing amount of tractors. This is to say that countries like Australia, Canada, and the United States have the highest labor productivity but also the largest use of machinery and the largest use of arable land per farmers—the three things go together. Actually, the major increase in productivity of labor in these countries can be associated to a major increase in the use of machinery, e.g., Australia had an increase of 100% in the crop output: from 700 MJ/worker/year in 1991 to 1400 MJ/worker/year in 2003. The possibility of intensifying the use of tractor per farmers, however, depends on the availability of a huge amount of arable land (e.g., more than 100 ha) per agricultural worker.

Different is the situation of the other European countries where agriculture is evidently subject to severe biophysical constraints in terms of shortage of arable land per farmer (when compared with Australia or the United States), a consequence of demographic pressure.

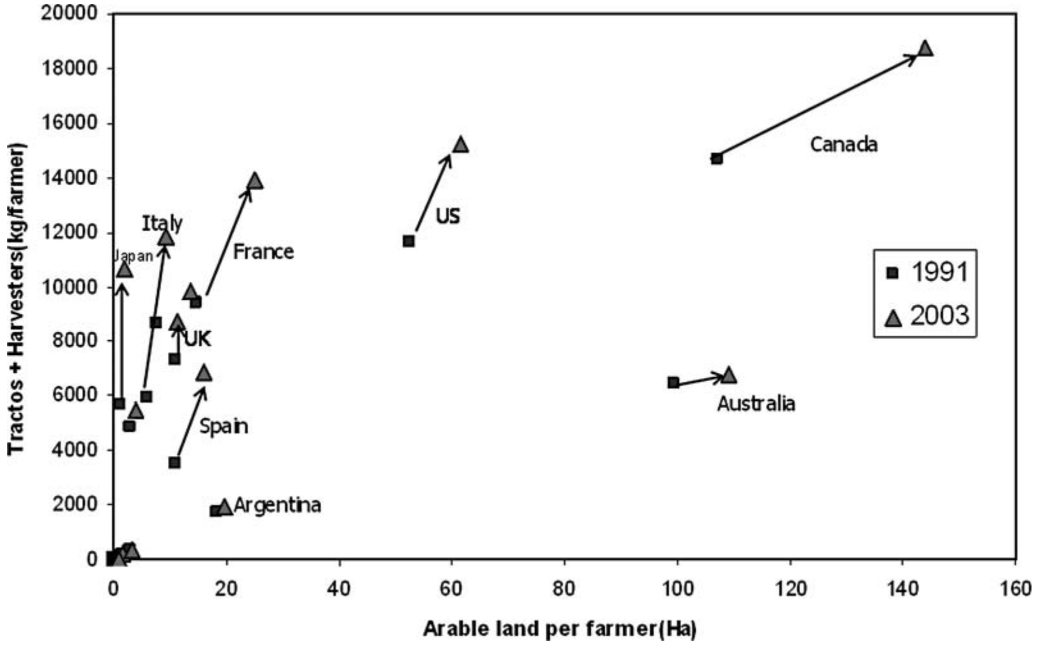

FIG. 10. Arable land versus tractors-harvesters.

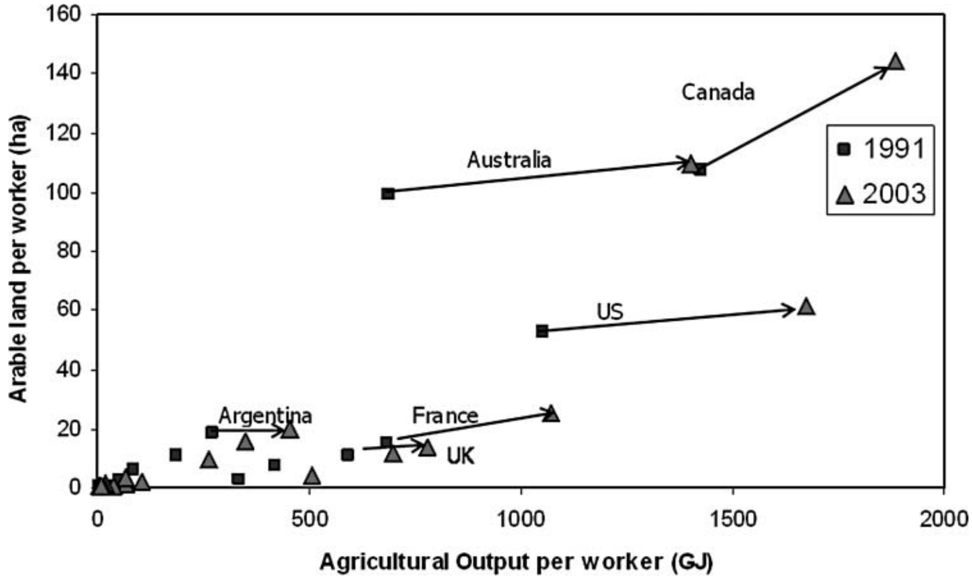

FIG. 11. Agricultural output versus arable land.

E. Technological Inputs and Demographic and Bio-Economic Pressure

The relationship between productivity of land and productivity of labor in agriculture is depicted in Figure 12 and reveals some interesting trends. For instance, the United States and Canada agriculture have a lower performance in terms of yield per hectare than agriculture in Bangladesh, China, Costa Rica, Ghana, Egypt, and the European Union.

On the other hand, U.S. agriculture has the best performance in terms of labor productivity. China, with its huge population, suffers such a severe shortage of arable land that all technological and fossil energy inputs appear to go into raising land productivity with little regard for farm labor productivity.

The Netherlands and Egypt have a high land productivity increasing from 1991 to 2003 as well as the labor productivity. This pattern, however, is not present in other countries. These data indicate that for the 21 agricultural systems studied, the purpose of energy and technological inputs used in agriculture is not necessarily the same. Differences are related to different definitions of ‘efficiency’ for agriculture depending on the different levels of bio-economic and demographic pressure affecting societal choices.

F. The Overall Pattern of Energy Consumption in Agriculture

The consumption of fossil energy in agriculture can be divided in two categories: direct and indirect. Direct consumption of energy refers to the consumption of fuels for operating machineries, irrigation pumps, heating greenhouses and the moving loads, the consumption of electricity for drying crops, heating and illumination—that is energy spent in the agricultural sector. Indirect consumption of fossil energy refers to the energy spent in the industrial sector for the production of the technological inputs used in agriculture. This indirect consumption includes the production of fertilizers and pesticides (in the chemical sector), the fabrication of machinery (in the mechanical sector) and the fabrication of other infrastructures. For this reason, it is normal to find a discrepancy between the estimates of energy consumption of the agricultural sector found in national statistics and the estimates based on the accounting of direct and indirect fossil energy consumption, which include also the embodied energy in the technical inputs.

To clarify this issue, an overview of the contribution of the different forms of energy is provided in Table 3. In relation to the calculation of this table, we assumed in other inputs a flat rate of 5% of the sum of other technical inputs required for primary production; for example, infrastructure (commercial buildings, fences), electricity for on-farm operations (e.g., drying of crops), energy for heating and energy inherent in use of vehicles and fuels for transportation (Giampietro, 2002).

When interpreting this data set against the rationale adopted in this study, we can observe that countries with high GDP per capita and high demographic pressure, such as Japan and the Netherlands, have a high consumption of fossil energy both per hectare and per worker. Countries with high GDP per capita but relatively low demographic pressure, such as the United States, Canada, and Australia, have high consumption of fossil energy per farmer (to achieve high labor productivity) but relatively low energy consumption per hectare of arable land. Between these countries we can observe in European countries like France, UK, Germany, Italy and Spain. The opposite is true for countries with high population density and low per capita income, such as China and Egypt, which basically invest important amount of fossil energy, but only to boost the productivity of food per hectare.

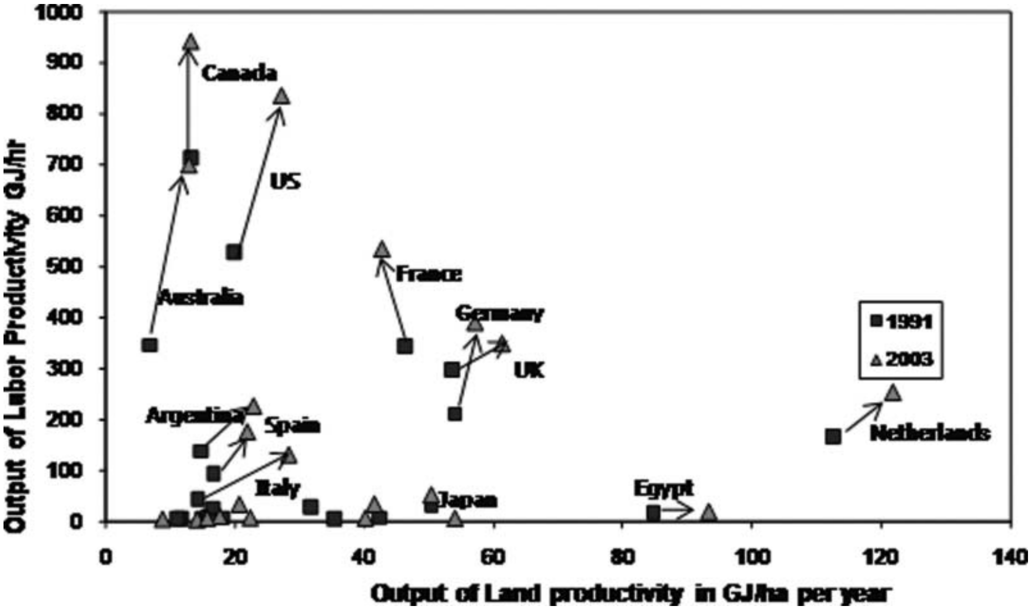

FIG. 12. Output of land productivity versus output of labor productivity.

This observation suggests that we should expect a mosaic of different solutions to the challenge of a sustainable food production, especially when considering that other biophysical constraints, e.g., availability of water, soil, climatic conditions, and ecological constraints, e.g., the level of destruction of natural habitats, which are needed for biodiversity preservation, are different in different areas of the world. This is to say, that it is not reasonable to expect that the future technical progress of agriculture, even when discussing of agro-ecological solutions should be obtained by implementing a common pattern all over the world. Rather than looking for technological packages to be applied all over the planet (extensive adaptation), without regards for the local specificity, we should be looking for specific solutions tailored on the specificity of different situations. When dealing with the sustainability of agriculture “one size does not fit all.”

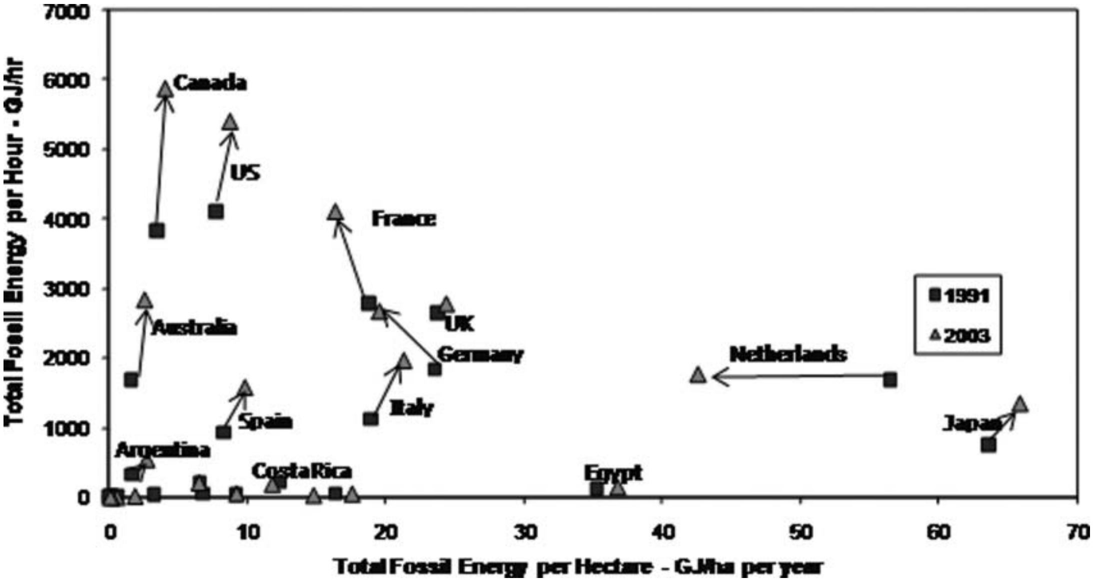

FIG. 13. Total fossil energy per hectare versus per hour.

TABLE 3

Fossil energy input in agricultural production for selected countries

	Indirect Energy Inputs										Direct Energy Inputs													
	Nitrogenous (PJ)		Phosphate (PJ)		Potash (PJ)		Machinery (PJ)		Pesticides (PJ)		Total Indirect Indirect (PJ)		Irrigation (PJ)		Fuel (PJ)		Other inputs (PJ)		Total Direct (PJ)		Estimated Grand Total (PJ)		Reported in Statistics (PJ)	
	1991	2002	1991	2002	1991	2002	1991	2002	1991	2000	1991	2002	1991	2002	1991	2003	1991	2003	1991	2003	1991	2003	1991	2003
Argentina	13,1	13,1	0,9	4,9	0,2	0,3	25,8	28,0	0	0	40,1	46,3	13,1	13,1	50,8	55,1	5,2	5,7	69,1	73,9	109,2	120,1	69,0	113,4
Australia	0,4	0,4	11,8	18,7	1,9	3,1	29,8	29,7	50,3	0,0	94,2	51,9	0,4	0,4	58,7	58,5	7,7	5,5	66,7	64,4	160,9	116,3	46,2	77,7
Bangladesh	25,3	38,5	3,8	3,9	1,1	2,0	0,4	0,4	1,2	2,7	31,9	47,5	25,3	38,5	0,7	0,7	2,9	4,3	28,9	43,6	60,8	91,0	11,2	24,9
Burundi	0,7	0,7	0,02	0,01	0,01	0,01	0,01	0,01	0,1	0,1	0,8	0,8	0,7	0,7	0,02	0,02	0,1	0,1	0,8	0,8	1,6	1,7	—	
Canada	6,0	6,6	10,3	11,1	4,5	4,7	70,9	67,9	0	0	91,7	90,2	6,0	6,6	199,4	190,9	14,9	14,4	220,3	211,8	312,0	302,0	84,6	94,2
China	405,0	459,8	126,5	172,3	32,9	57,3	67,2	108,6	0,1	0,02	631,6	798,1	405,0	459,8	113,4	183,3	57,5	72,1	575,8	715,2	1207,4	1513,2	463,4	718,9
Costa Rica	0,7	0,9	0,3	0,6	0,5	0,9	0,6	0,7	0	16,9	2,1	19,9	0,7	0,9	1,2	1,3	0,2	1,1	2,1	3,3	4,1	23,2	1,4	4,8
Egypt	25,4	32,7	2,6	2,5	0,5	0,8	4,9	7,4	4,6	0	38,1	43,3	25,4	32,7	8,3	12,4	3,6	4,4	37,3	49,6	75,3	92,9		1,9
France	17,6	21,8	21,8	12,7	23,8	13,0	122,6	108,4	35,8	40,9	221,6	196,7	17,6	21,8	241,3	213,4	24,0	21,6	282,9	256,8	504,5	453,5	118,3	94,7
Germany	4,0	4,1	9,0	5,7	10,0	6,5	131,3	86,3	23,3	24,3	177,6	126,8	4,0	4,1	258,5	169,9	22,0	15,0	284,5	189,0	462,1	315,8	103,5	70,0
Ghana	0,1	0,1	0,0	0,1	0,0	0,1	0,3	0,3	0,0	0,1	0,4	0,7	0,1	0,1	0,6	0,5	0,1	0,1	0,7	0,7	1,1	1,4	1,6	8,2
India	397,0	478,7	57,7	69,5	18,6	22,2	85,3	202,6	59,4	0,0	618,0	773,1	397,0	478,7	143,9	341,9	57,9	79,7	598,8	900,3	1216,8	1673,4	54,6	241,5
Italy	22,7	23,0	11,5	6,5	5,7	3,7	120,3	137,4	71,5	63,2	231,6	233,8	22,7	23,0	236,8	270,5	24,6	26,4	284,0	319,9	515,7	553,7	103,5	117,1
Japan	23,6	21,8	12,1	8,4	6,6	4,6	250,8	245,6	0	0	293,1	280,4	23,6	21,8	423,2	414,5	37,0	35,8	483,9	472,1	777,0	752,5	89,6	117,2
Mexico	48,5	52,9	6,6	6,1	1,2	2,5	26,9	27,8	0	0	83,2	89,3	48,5	52,9	53,0	54,7	9,2	9,8	110,8	117,5	194,0	206,7	73,1	89,8
Netherlands	4,7	4,7	1,3	0,9	1,3	0,9	15,0	12,4	0	0	22,3	18,9	4,7	4,7	29,5	24,4	2,8	2,4	37,0	31,6	59,3	50,5	11,8	20,7
Spain	28,4	31,6	8,7	10,4	5,2	6,6	64,4	79,5	13,4	15,0	120,0	143,2	28,4	31,6	126,7	156,6	13,8	16,6	168,8	204,8	288,9	348,0	62,0	85,8
Uganda	0,1	0,1	0,01	0,05	0,01	0,03	0,4	0,4	0,1	0,0	0,5	0.5	0,1	0,1	0,6	0,6	0,1	0,1	0,8	0,8	1,3	1,3	—	
UK	1,4	1,4	6,3	4,9	6,0	5,1	43,8	43,8	25,0	26,5	82,6	81,7	1,4	1,4	86,3	86,2	8,5	8,5	96,2	96,0	178,8	177,7	33,4	12,8
US	174,9	188,3	66,4	67,3	0,0	0,0	416,4	433,8	171,6	0,0	829,4	689,4	174,9	188,3	1171,1	1220,0	108,8	104,9	1454,8	1513,2	2284,2	2202,5	609,4	641,3
Zimbabwe	1,0	1,1	0,7	0,5	0.4	0,3	1,5	0,1	2,2	0,0	5,8	2,0	1,0	1,1	2,5	0,1	0,5	0,2	4,0	1,4	9,8	3,4	2,9	37,5

Source: Giampietro (2002) and calculations on FAOSTAT.

Reported In Statistics: Data from IEA World Energy Statistics and Balances considering Agriculture/Forestry - Petroleum Products.

IV. CONCLUSION

The analysis presented in this paper clearly shows the existence of huge differences in the situation experienced by farmers operating in different contexts (e.g., developed countries versus developing countries; very populated countries versus sparsely populated countries). These differences may be further boosted, in the future, by existing trends of demographic and economic growth. In fact, there are countries in Africa and in America and Asia where population is still growing faster than GDP and countries where the GDP is growing faster than population.

When considering socioeconomic constraints, due to the required high level of investment per farmer (Giampietro, 2008; Giampietro and Mayumi, 2009), in many developing countries it would be impossible to follow the "Paradigm of Industrial Agriculture" which has been implemented in developed countries. In fact, replacing the work of farmers with expensive pieces of machinery and huge injections of technical inputs requires the availability of a lot of capital, the existence of consumers capable of buying expensive food, and the possibility of absorbing the vast majority of rural population into cities where they can work in the industrial or the service sector with productivity that (in economic terms, not in physical terms) is higher than in the villages they left behind. Many developing countries do not have enough money to invest in a capitalization of their agriculture, nor rich consumers which can buy expensive food, nor an economy which can offer well paid jobs in the cities. This point is in favor of alternative techniques of production based on a low dependence on external inputs. As a matter of fact, when looking at the changes in the use of technological inputs over the time window considered in this study, we can notice that tractors, nitrogen and irrigation have increased at the world level, but at considerable different rates in Africa and Europe.

When considering biophysical constraints, a continuous increase in demographic pressure results in the requirement of a continuous increase in food production. Since the best arable land is already in use, this translates into the need of bringing new land under production, expanding irrigated land area and applying Green Revolution technologies also on marginal land. In many countries in Africa, Asia and some countries in South America this translates into a continuous expansion of agricultural production into fragile and ecologically sensitive regions, where yields are lower than in fertile land. This requires a larger use of technical inputs with lower economic return and a much larger environmental impact in terms of loss of habitat for biodiversity preservation. To make things worse, economic development not only tends to reduce the number of farmers, but also to change the mix of food products in the diet of the growing urban population. As a consequence of this fact, in developing countries more people are eating more animal products (dairy and meat). This translates into an increasing quantity of grains consumed per capita, for the supply of animal products. That is, the combination of population and economic growth translates into a major boost in the requirement of food production, and therefore a major boost to the stress on terrestrial and aquatic ecosystems.

Nobody can predict the future of agriculture in 50 years from now. What we can say is that it is very unlikely that the future technical development of agriculture will continue by doing "more of the same" as done right now. For this reason it is important to study alternative systems of agricultural production capable of generating a diversity of performances, which can be selected in different contexts in relation to different criteria and different typologies of constraints.

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