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The issues of energy and carbon cycle: new perspectives for assessing the environmental impact of animal waste utilization

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Abstract

This paper focuses on the benefits of an efficient use of animal waste from the standpoint of curbing the rise of anthropogenic carbon dioxide (CO_2) in the atmosphere. An effective use of animal waste resources might provide a partial, but still important, contribution in reducing net CO_2 emissions. In particular: the fulfilment of nutrient requirements of crop plants growing in non-limiting conditions and thus sequestering CO_2 at their potential level; the chance of diminishing the use of fossil energy, and related CO_2 emissions, required for manufacturing industrial fertilizers; the possibility of enhancing carbon sequestration in agricultural soils by the application of farmyard manure. The future success of agriculture in providing these ecosystem services can only be achieved with a changed social awareness of the links between sustainable land use and global environmental change.

Keywords: Manure; Industrial fertilizers; Use of fossil energy; Anthropogenic CO_2 emissions; Crop CO_2 sequestration; Crop management

1. Introduction

All intensive livestock systems cause serious problems of waste utilization. For the purpose of feeding animals, huge amounts of plant biomass harvested over large areas are concentrated on small areas. The problems arise because the animal excreta are characterized by high water content, so the restitution of mineral nutrients to the original land is both energy intensive and expensive. Begon et al. (1996) defined these problems as being among the most intractable that any ecologist can face. Until now, the overwhelming environmental concerns regarding animal waste utilization have been focused on nutrient accumulation in the arable soil profile, contamination of surface and groundwater and ammonia emission into the atmosphere. Yet, during the last decade, there has been growing concern about the environmental consequences of a massive use of fossil energy and the related increase in CO_2 in the atmosphere. The Inter-governmental Panel on Climate Change (IPCC, 1996) indicated that the risks of climate change induced by greenhouse gases are so serious as to justify immediate action. On the basis of recent estimates (Prentice et al., 2001) the rise of CO_2 concentration in the atmosphere is primarily due to the consumption of energy from fossil fuel burning, whereas a fraction of 10–30% can be attributed to land-use changes.

European countries under the Kyoto protocol are committed to reducing CO_2 emissions during the period 2008–2012 to 92% of the reference level of the year 1990 (UNFCCC, 1998). Thus, in aiming to reach the target of reducing anthropogenic sources of CO_2 emission, any human activity should be analysed to identify gains in energy efficiency and energy reduction measures. Within this framework, the contributory role of agriculture is twofold: in the first instance, reduction of CO_2 emissions can be achieved by reducing the rate of fossil energy use for agricultural management (chiefly production of fertilizers, pumping irrigation water and soil tillage); in the second instance, the adoption of high-yielding crops with appropriate crop rotation, manure application and reduced tillage can improve CO_2 crop sequestration and subsequent soil storage (Lal, 2002). Hence, within the overall role of agriculture, an efficient use of animal waste might make its own contribution. The scope of this paper is to highlight some interconnections between animal waste utilization, the use of fossil energy and the carbon cycle. The following environmental issues are addressed:

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- the positive impact of an effective use of manure in reducing fossil energy consumption and CO_2 emission for the industrial production of fertilizers;
- the negative impact of transporting and/or drying manure using fossil energy in order to reduce the accumulation of nutrients in livestock areas;
- the capacity of well-managed crops to sequester atmospheric carbon, whilst utilizing nutrients, making use of solar energy.

2. The positive impact of an effective use of manure in reducing fossil energy consumption and CO_2 emission for the industrial production of fertilizers

Sangiorgi (2000) emphasized the potential role of manure for saving the fossil energy required in the industrial production of mineral fertilizers. This aspect has been neglected since fossil energy was abundantly available at low cost and concern about the emissions of greenhouse gases was limited. The present concern about global climate change should stimulate practical solutions, and policy actions, aimed at reducing the dependence of agriculture on industrial fertilizers by increasing efficiency in the use of manure.

Helsen (1992) reported that 76.3 $MJ\,kg^{-1}$ N are required to produce urea, which is the most energy-demanding but also the most widely used N fertilizer in the world. Consequently, if 300 $kg\,N\,ha^{-1}$ are applied as urea to a maize crop (*Zea mays* L.), the fossil-energy cost is 22890 MJ. Given the energy content of 38.66 $MJ\,l^{-1}$ of diesel fuel (Pimentel, 1992) about 592 l of diesel fuel are needed solely for N fertilization. In addition, the production of granulated superphosphate requires about 8.6 $MJ\,kg^{-1}$ P_2O_5, and about 6.4 $MJ\,kg^{-1}$ K_2O. Therefore, when 100 kg of P_2O_5 and 100 kg of K_2O are also applied, another 38 l of diesel fuel are needed, bringing the total amount to 630 l. Given the density of 0.781 $kg\,l^{-1}$ of diesel fuel, 630 l correspond to 492 kg. Kramer et al. (1999) estimated that the use of 1 kg of diesel fuel determines the emission of 3.56 kg CO_2, 5.2 g CH_4, and 0.7 g N_2O, also taking into account the emissions required for the extraction and delivery of the unit of energy.

It is convenient to refer to the total emissions in terms of CO_2 (the reference gas) by multiplying CO_2 by 1, CH_4 by 21, and N_2O by 310 (IPCC, 1996). These multiplying factors account for the greenhouse effect of each individual gas. This leads to a total emission of 3.89 kg CO_2 kg^{-1} of diesel fuel, inclusive of the quota necessary for extraction and delivery. Consequently, 492 kg of fossil fuel determine the emission of about 1914 kg of CO_2 equivalent.

On the basis of the above calculations, the amounts of N, P and K absorbed by the crops via manure application have a "fossil-energy substitution value" as opposed to the energy demands of industrial fertilizers. In addition, it is important to point out that any methods of collection, storage and distribution of manure that allow nitrogen to be conserved by reducing ammonia volatilization, can also be seen as environmental friendly also from the viewpoint of the carbon cycle.

3. The negative impact of transporting and/or drying manure using fossil energy in order to reduce the accumulation of nutrients in livestock areas

The implicit condition of the previous statements is that the energy necessary to deliver nutrients to the recycling crops should be as limited as possible. In terms of energy consumption, manure transportation appears to offer some viable alternatives to the manufacturing of industrial fertilizers. In fact, the energy required for transportation of a manure, with a given content of N, can be compared with the energy required for manufacturing an equivalent amount of N in form of mineral fertilizer.

Transportation by truck of 1 t requires 3.47 $MJ\,km^{-1}$ (Pimentel, 1992). Then, if a liquid pig manure with 3 $kg\,N\,t^{-1}$ is taken as reference, and bearing in mind the energy required for the industrial production of 1 kg N in form of urea (76.3 MJ) the energy cost for 3 kg N in the form of urea ($76.3 \times 3 = 228.9$ MJ) is equivalent to that necessary for the transportation of 1 t of manure for about 66 km (i.e. $228.9/3.47 = 65.97$ km). It is clear that manure with a higher concentration of nutrients could be conveniently delivered over longer distances. Therefore, any solution that prevents the dilution of manure (e.g. by avoiding the addition of rainwater) can be regarded as environmentally friendly form the standpoint of mitigating CO_2 emissions.

Unfortunately, from an economic point of view, it is quite evident that, given the current price situation, there is no economic advantage in paying for the transportation of pig slurry instead of purchasing urea. In fact, referring to the situation of May 2002 in Modena (Italy), the price of prilled urea (46% N) is 204 Euro t^{-1}, corresponding to 0.502 Euro kg^{-1} N (Camera di Commercio di Modena, 2002). Moreover, on the basis of local reference price for the year 2002 (APIMA, 2002) transportation by truck of 44 t of pig slurry costs 99 Euro h^{-1}. Considering the reference pig slurry with a content of 3 $kg\,N\,t^{-1}$, 44 t contains 132 kg N, so the cost of transportation is $132/99 = 1.33$ Euro kg^{-1} N.

However, it is important to stress that present economic conditions, which until now have been essentially driven by the market, could be modified by policy measures like levies on the use of industrial fertilizers, or direct subsidies for using manure in the place of industrial fertilizers. Nowadays, technology is available to separate manure into clean water, N–P–K liquid concentrate, and dry matter. The Manura 2000® system (Funki, 2001) separates pig slurry into clean water, dry organic fertilizer, liquid NPK fertilizer and liquid N fertilizer. The treatment is performed in three steps: mechanical pre-separation, concentration by evaporation and purification of the distilled water. The power consumption of the system is approximately 50 $kW\,h^{-1}\,m^{-3}$ of slurry. The production of electricity has an emission factor of 0.834 kg CO_2 $kW\,h^{-1}$ (IPCC, 1997; Pluimers et al., 2001); therefore the treatment of 1 t involves an emission of $50\times0.834 = 41.7$ kg CO_2, then 13.9 kg CO_2 kg^{-1} N for a diluted pig slurry with 3 kg N t^{-1}. This is a high estimates, however, for its assumption that all electricity was produced by coal-fired power plants. In reality, part of the electricity is produced by gas- or oil-fired power plants with lower CO_2 emissions. Furthermore, electricity generated by hydro-electric and nuclear power plants is free of CO_2 emissions.

4. The capacity of well-managed crops to sequester atmospheric CO_2, whilst utilizing nutrients, making use of solar energy

A field crop growing without limitations of water and nutrients is the ideal situation for efficient uptake and recycling of nutrients from animal wastes. Since this is also true for atmospheric CO_2 sequestration in plant biomass, then nutrient recycling, carbon sequestration and crop biomass yield are positively interdependent.

A maize crop, growing under non-limiting conditions, has a daily net assimilation of about 500 kg CO_2 ha^{-1}, corresponding approximately to all the CO_2 contained in a volume of air up to a height of 100 m above the crop area (Loomis and Amthor, 1999). In fact, the average daily growth rate for maize is about 300 kg dry matter ha^{-1} with a content of 44% of carbon. This is equivalent to 132 kg C ha^{-1}, the ratio C/CO_2 is $12/44 = 0.27$, so $132/0.27 = 484$ kg CO_2 ha^{-1}.

It is possible to gain additional insight on the "sequestering C service" of a maize crop, growing in potential production conditions, by integrating daily net CO_2 assimilation throughout the growing season with a simulation model. The example shown in Fig. 1 refers to a maize crop in the Po Valley. A maize crop, with a grain yield of 11.5 $t\,ha^{-1}$, and total aboveground biomass of 21.9 $t\,ha^{-1}$, has a total net CO_2 assimilation of 41.5 $t\,ha^{-1}\,year^{-1}$. Simulation was performed with the model Sucros 97 (Van Laar et al., 1997), after calibration with locally collected data (Ceotto, 1999). Actual daily meteorological data from S. Prospero (Modena) were used for simulation.

The model Sucros 97 (Van Laar et al., 1997) used for simulation, estimates crop dry matter accumulation as a function of solar radiation, air temperature and crop characteristic, assuming abundant availability of water and nutrients, and the absence of pests, diseases and weeds. The basic process for dry matter accumulation is the CO_2 assimilation that uses the photosynthetically active solar radiation intercepted by the green leaf area as a source of energy. Part of the carbohydrates production is used for maintenance respiration, while the rest is converted into the structural biomass of plant organs. Maintenance costs depend on dry matter weight and maintenance coefficient of leaves, stems and storage organs, and they are also increased by a rise of temperature. The partitioning of biomass into plant organs is a function of the development stage of the crop, which in turn is temperature-dependent. The conversion of

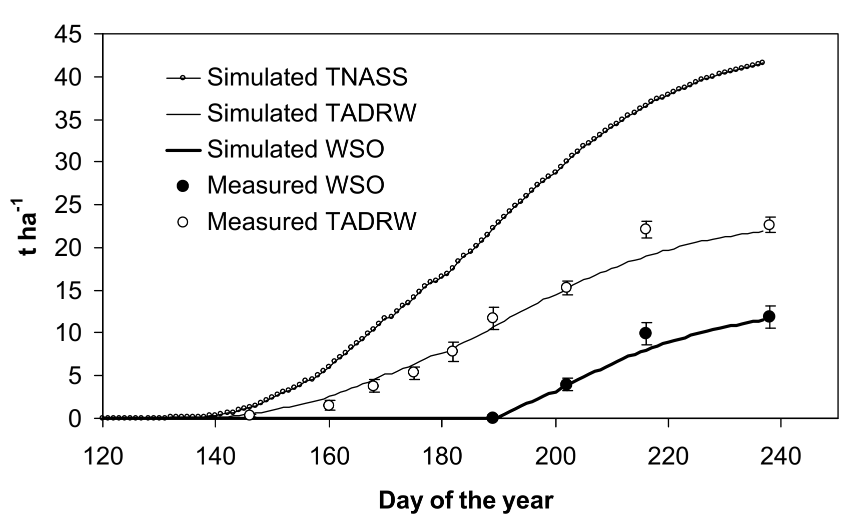

Fig. 1. Simulated and measured time course of a maize crop in the Po Valley. TNASS = total net CO_2 assimilation; TADRW = total aboveground biomass; WSO = weight of storage organs. All data points are the average values of two independent sampling. Bars indicate ± standard error of the mean.

carbohydrates into structural plant organs determines loss of weight (growth respiration) depending on the relative composition of the organs in terms of sugars, proteins, fat and lignin. Growth respiration is temperature independent. The net result of total gross CO_2 assimilation and total respiration losses due to maintenance and growth is the total net CO_2 assimilation (TNASS).

It is important to emphasize that the total net CO_2 assimilation of the sample maize crop (41.5 t CO_2 ha^{-1} $year^{-1}$) amply makes up the emissions involved in the production of the mineral fertilizers used to sustain its growth (1914 kg CO_2 ha^{-1} $year^{-1}$). Still, it is interesting to quantify here the CO_2 emissions related to pumping the irrigation water necessary to sustain high crop yield. Follett (2001) reported an emission of 236 kg C ha^{-1} $year^{-1}$ for irrigation pumping using diesel as energy source, equivalent to $236/0.27 = 874$ kg CO_2 ha^{-1} $year^{-1}$. So, the overall CO_2 emissions for mineral fertilizers and irrigation pumping is $1914 + 874 = 2788$ kg CO_2 ha^{-1} $year^{-1}$, which is about 6.7% of total net CO_2 assimilation of the maize crop cited.

In literature, several energetic analysis of cropping systems highlighted that nitrogen mineral fertilization is the most energy demanding agronomic practice, but on this basis, very different conclusions were promulgated. Altieri (1995) pointed out that modern agro-ecosystems, owing to their dependence on fossil energy, are vulnerable and less energy efficient with respect to low-input farming. In contrast, Loomis and Connor (1992) demonstrated that mineral fertilizers can be seen as a substitution of energy for land, because with low fertilization more cultivated land is necessary to obtain the same production. This is also consistent with the analysis of carbon balance presented in this paper.

Nevertheless, the role of manure in gaining efficiency in the carbon balance is still important. In fact, most of the nutrient requirements could be fulfilled by manure, maintaining equal levels of crop CO_2 sequestration on the one hand, and diminishing the CO_2 emissions related to production of industrial fertilizer on the other. A judicious use of chemical fertilizers at the right time, however, is still necessary to match the crop requirements for high levels of biomass production and carbon sequestration (Lal, 2000).

The Kyoto protocol, signed in December 1997, introduced the concept of credit for C sinks, and recognized credits for afforestation and reforestation (Article 3.3) but not for other agricultural land use. Indeed, Article 3.4 of the protocol mentioned the possibility of future inclusion for other agricultural activities, under conditions of transparency and verifiability. The initial objection against inclusion of agricultural activities was due to the uncertainties in assessing the amount of carbon that can actually be sequestered in agricultural soils. The subsequent Bonn agreement (COP6) and Marrakech accords (COP7) established that agricultural sinks will be included (UNFCCC, 2002).

In fact, young and fast-growing forests can act as effective carbon sinks by accumulating carbon in both vegetation and soil (Rosen et al., 2000). Nevertheless, recent studies have raised serious doubts about the real efficiency of forests in CO_2 sequestration. Oren et al. (2001) pointed out that forests are usually relegated to soil with poor fertility, and that therefore tree growth is often limited by nutrients and/or water availability. Furthermore, Schlesinger and Lichter (2001) reported that half of the carbon uptake of the forest is allocated to short-lived tissues (i.e. leaves), and that carbon accumulation in deeper soil layers is virtually absent. Conversely, it is important to emphasize here that a well-managed crop does not suffer these limitation, and in case of maize, can take advantage of the C4 pathway that assures one third higher production efficiency.

Of course, enhancing carbon sequestration in crop biomass is only the first step; the subsequent management of crop residues in order to increase the amount of stable soil organic matter (SOM) is of paramount importance. In fact, farmyard manure application, residue mulching and conservation tillage offer opportunities for enhancing carbon sequestration in agricultural soils. Lal (2000) estimated that soil carbon sequestration has the potential to reduce the rate of increase in atmospheric CO_2 concentration over the next 50 year period.

On the basis of land management scenario studies for European cropland, Smith et al. (2000) estimated an important mitigation potential for the use of manure, although the potential mitigation of no-till and bio-energy crops was considerably higher. They concluded that an appropriate combination of land management practices offers considerable potential for carbon mitigation, although no single land management initiative itself can meet the requirements of European carbon mitigation commitments.

Referring to USA cropland, Follett (2001) estimated that an annual application of manure equivalent to 250 kg N ha^{-1} would lead to an annual increase of 200–500 kg C ha^{-1} in the arable soil profile. Schlesinger (1999), on the other hand, was sceptical about the role of manure in contributing to yield a net sink for carbon in SOM. He focused on the "hidden carbon costs", related to manufacture and delivery of fertilizers, as against the final gain of carbon in SOM. Nevertheless, his arguments appear to ignore the fact that the annual carbon costs for agricultural practices are amply compensated by the annual carbon sequestration performed by the crop plants.

Magette (2000) pointed out that the "polluters pay" principle is a well-established guideline in the EU legislation. So, if this principle were to be extended to greenhouse gas emissions, a trade could be established by transferring payments from CO_2 polluters to "CO_2 sequesters". Likewise, Izaurralde et al. (2000) remark that if carbon stored in agricultural lands could become a tradeable commodity, then environmentally sound management practices might be effectively encouraged.

However, Woerdman and van der Gaast (2001) pointed out that the inclusion of agricultural sinks in emission trading mechanisms comes up against technical and political problems. The technical problem has to do with the fact that methods for evaluating changes in soil organic carbon lack precision and takes long time for verification. The political problem arose when some countries expressed their concern that inexpensive sinks projects could displace efforts to reduce emissions in the industrial and transportation sectors.

5. Future challenges

Agricultural systems provide a wide variety of goods and services for human society (Rosen et al., 2000). In addition to economic yield, cropping and farming systems are crucial to greenhouse gas regulation and nutrient recycling. These important functions contribute to the quality of the environment and human welfare, yet they are outside of the market and still receive too little consideration in policy decisions (Costanza et al., 1997). Thus, an important challenge for agro-ecological research is to make the value of ecosystem services, in particular carbon sequestration and nutrient recycling, more apparent. In this context, an effective use of animal waste resources might provide the following important contributions:

- the fulfilment of nutrient requirements of crop plants growing in non-limiting conditions and thus sequestering atmospheric CO_2 at potential level;
- the chance of reducing the use of fossil energy, with its related CO_2 emissions, necessary for the manufacturing of industrial fertilizers;
- the possibility of enhancing carbon sequestration in agricultural soils by application of farmyard manure to optimized cropping systems.

It is important to note that the above environmental services are benefits for the society as a whole but are of little direct utility for the farmers. In addition, farmers are responsive to economic forces and not to energy or carbon balances. Therefore, the future success of agriculture in providing these services will depend on whether the farmers will be economically motivated and supported in their efforts to practice environmentally sound land use. Tilman et al. (2002) pointed out that the actual agricultural subsidies in the United States, EU and Japan need to be reoriented to support the adoption of sustainable farming practice at large scale. This requires a "willingness to pay for environmental services" at society and individual levels that can only be achieved with a changed awareness of the links between agro-ecosystem functions and global environmental change.

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