REVISÃO DE LITERATURA

THE COSTS OF SOIL EROSION[(1)]

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ABSTRACT

The aim of this study was a survey of the estimated costs of soil erosion, an issue of fundamental importance in view of the current worldwide discussions on sustainability. A list was drawn up of research papers on erosion (on-site and off-site effects) and their respective costs. The estimates indicate the amount of resources spent in the process of soil degradation, raising a general awareness of the need for soil conservation. On-site costs affect the production units directly, while off-site costs create a burden borne by the environment, economy and society. In addition, estimating the costs of soil erosion should be effective to alert the agricultural producers, society and government for the need for measures that can be implemented to bring erosion under control. Among the various estimates of soil erosion costs between 1933 a 2010, the highest figure was 45.5 billion dollars a year for the European Union. In the United States, the highest figure was 44 billion dollars a year. In Brazil, estimates for the state of Paraná indicate a value of 242 million dollars a year, and for the state of São Paulo, 212 million dollars a year. These figures show, above all, that conservation measures must be implemented if crop and livestock farming production are to be sustainable.

Index terms: soil degradation, on-site and off-site losses, sustainable development.

RESUMO: *OS CUSTOS DA EROSÃO DO SOLO*

Este estudo teve por objetivo realizar uma revisão sobre as estimativas dos custos da erosão do solo – um levantamento de fundamental importância diante das discussões sobre sustentabilidade ao redor do mundo. Para isso, foram elencadas pesquisas sobre os efeitos on-site e off-site e seus respectivos custos. Essas estimativas apontam o montante de recursos

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gastos com o processo de degradação dos solos, criando um senso comum sobre a necessidade de sua conservação: os custos on-site, porque alteram diretamente a unidade produtiva; e os off-site, porque geram ônus ao meio ambiente, à economia e à sociedade. Além disso, as estimativas dos custos da erosão do solo contribuem para alertar produtores, sociedade e governo sobre a busca de medidas e ações para seu controle. Entre as diferentes estimativas dos custos da erosão do solo, realizadas entre 1933 e 2010, a maior foi de 45,5 bilhões de dólares ao ano, para a União Europeia. Nos Estados Unidos, os valores chegam a 44 bilhões de dólares ao ano. No Brasil, no Estado do Paraná, atingem 242 milhões de dólares ao ano, e no Estado de São Paulo, 212 milhões de dólares ao ano. Esses valores mostram, acima de tudo, que medidas conservacionistas devem ser tomadas para que o sistema de produção agropecuário seja sustentável.

Termos de indexação: degradação do solo, perdas on-site e off-site, desenvolvimento sustentável.

INTRODUCTION

Soil erosion is not only an agricultural problem. It is associated with a host of environmental, social and economic issues. It has also been acknowledged as a major setback for food security and a serious problem for sustainable development.

The soil is eroded by the action of water and wind which break up and disperse soil particles (Miller, 1931; Bennett, 1955; Foth, 1990). One of the factors that accelerate this process is inappropriate soil management, a human activity documented in numerous studies, including those of Bennett (1929), Ellison (1948), Lal (1997), and Bertoni and Lombardi Neto (2008). Water erosion affects most of the planet and is the result of rainfall and surface runoff, aggravated mainly by agricultural management systems (Zachar, 1982). Erosion alters the soil chemical, physical and biological properties, reducing soil fertility and, as a direct result, soil productivity (Pimentel et al., 1995; Lal, 2000, 2006; Morgan, 2005), which has caused concern among researchers in various fields about the losses and costs incurred.

Costs are calculated on the basis of *on-site* effects (losses within the productive unit) and *off-site* effects (damage caused beyond the agricultural property). In the United States, the annual cost of soil erosion for both on-site and off-site effects has been estimated at 44 billion dollars a year (Pimentel et al., 1995). In the European Union, the figure is 38 billion Euros a year (Montanarella, 2007).

In Brazil, although soil conservation is a respected and well-established science, there are few studies on the costs of erosion, which are normally restricted to few soil types and regions (Marques et al., 1961; Silva et al., 1985; Sorrenson & Montoya, 1989; Derpsch et al., 1991; Marques, 1998; Rodrigues, 2005; Bertol et al., 2007; Sarcinelli et al., 2009).

This study presents a survey of estimated soil erosion costs with a view to stimulate the discussion on the impact of soil erosion on the agricultural activity, environment, economy and society in general.

WHY CONSERVE THE SOIL?

The classic problem of the sufficiency of natural resources and provision of food to the population continues, even nowadays, to be very worrying and is currently being approached as a food security issue.

The relationship between natural resources and population was first mentioned in classical economics by Adam Smith in “The Wealth of Nations”, (Smith, 2008), and later developed by Thomas Robert Malthus in his book “An Essay on the Principle of Population”, (Malthus, 1999). Malthus based his argument on the fact that natural resources such as soil are limited and if conditions remain constant, the population tends to increase to the point at which there will not be enough food for everyone. In other words, while food production increases in arithmetic progression, population will grow in geometric progression. He concluded that production costs would not increase until all available land was being used. He also believed that arable land was of uniform quality.

David Ricardo introduced a few modifications into the Malthusian model in his book “On the Principles of Political Economy and Taxation” (Ricardo, 2006). He agreed that the amount of land was finite, but took its variability in terms of quality into account. According to his theory, the best land would be used first, and then poorer quality land would be used. As a consequence, production costs would increase excessively, before reaching the limit of farming land. The point at which costs would begin to rise and the speed of this increase would depend on the quality of the land available and the population increase, i.e. the demand.

As a result of changes brought about by the Industrial Revolution, these authors acknowledged the possibility of technological progress, but it was generally thought that this progress could at most delay the “fatal day”, but not solve the problem of scarcity of natural resources.

Technological evolution was the basis for the studies conducted by Barnett and Morse (1963).

According to the dynamic theory put forward by these authors, technological advances would make the shortage of natural resources improbable. However, not all economists accepted this argument, even when applied to technologically advanced countries (Simpson et al., 2005). Still, the role of technology in making resources available that would otherwise be inaccessible is important and widely acknowledged (Taylor & Young, 1985; Sampson & Knopf, 1994; Aldy et al., 1998; Pimentel et al., 1999). Nevertheless, neither technology nor value extracted from natural resources are free-of-charge, since many things are possible, but not all are economically viable (Reganold et al., 1990; Pretty & Ward, 2001). The soil can be revitalized when nutritive substances run out, even if part of the soil is lost through erosion or destroyed in some other way. But if this degenerative process is not interrupted, it could irreversibly compromise the productive capabilities of farming land (Lal, 2001; Gisladottir & Stocking, 2005).

Anthropogenic changes have often resulted in significant modifications of the soil productivity, either for better or worse (Bennett, 1940; Menzel, 1991; Pimentel et al., 1995; Knowler, 2004) and this has often obscured the dialog concerning soil conservation. There is an inability to differentiate periodic investments for current production from investments targeting alterations in the basic soil structure (Chavas & Aliber, 1993; Ruttan, 2002). For Bennett (1939), soil conservation is an issue of religion (faith and ethics) and economics (business and investment-return comparison). Following the same reasoning, Crosson (1985, 2007) considered conservation to be a question of values: an investment to maintain the level of production, reduce the deterioration of productivity and increase productive potential. However, land cannot be considered in isolation. It only becomes productive when combined with work, capital, production materials and a management system (Matsuyama, 1992; 1999; Uri, 1999; Chavas, 2001). A microeconomic analysis identifies a variety of combinations of production factors, although for many agricultural producers, these factors can be fixed.

Thus, soil conservation programs involve intertemporal, interspatial and interpersonal comparisons (Pagoulatos et al., 1989; Popp et al., 2001), as well as differences between production levels and trends (Barbier, 1997; Bergsma, 2000). Barlowe (1986) highlighted variations in future agricultural yields with and without investment in soil conservation. He stated that, if soil conservation is defined as the effort to modify a trend in soil productivity so as to make it better than it otherwise would be; this implies in a different distribution of investments and annual production than in cases in which the conservationist approach were not adopted. However, his analysis was carried out exclusively in terms of expected annual yield, and is valid only in these terms, since it does not take account of the possibility of land valuation as a result of the stabilization of productivity. If the land market were perfect, future differences in productivity would be directly reflected in current land value.

One important reason for conserving the soil is to increase earnings (Saliba, 1985; Pagoulatos et al., 1989). Due to the time lag between investment and production that conservation almost always involves, reliable comparisons should always be based on the current value and future costs (Hoag & Yong, 1986). This in turn necessarily involves a rate of interest or depreciation, which is always difficult to correctly assess (Wu et al., 1997). The balance between current values of investment and future earnings is a measure of the profitability of the conservation program chosen (Bennett, 1940; Chavas et al., 1983; Uri, 1999), and therefore, in the majority of cases, is an extremely important if not decisive factor.

For many farmers, the rate of depreciation is a matter of intuition, not calculation and estimation. This explains the well-established fact that they prefer immediate returns, rather than future profits. But soil conservation, or the lack of it, is not based solely on profitability.

A BRIEF HISTORY OF THE SOIL CONSERVATION MOVEMENT AND THE COSTS OF EROSION[5]

Although conservationist ideas have their roots in both Europe and the United States, we have opted in favor of the American movement, which has had a greater influence on soil conservation in Brazil.

Soil conservation in the United States, as an effective public program, commenced with the setting up of the "Soil Erosion Service", one of many "New Deal" programs introduced at the beginning of 1933. It was conceived by Hugh Hammond Bennett, who played a fundamental role in soil conservation between 1920 and 1950 (Bennett, 1929, 1933, 1935, 1939, 1940, 1955).

A few studies on soil erosion and related issues had already appeared before 1930. However, at that time, according to Bennett (1929) there was little clear and acceptable evidence of the nature and extent of the problems related to soil erosion. Furthermore, farmers as well as specialists were generally indifferent to the issue.

In its early stages, the soil conservation program was primarily concerned with encouraging research (practically the only activity until 1933), since so many

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factors are involved in soil erosion and their interactions are complex. A solid theoretical basis would be necessary to avoid mistakes and to convince skeptics. Moreover, at this time research was looked upon as a respectable activity in professional and political circles.

Initial research projects were focused on trying to measure soil losses under a variety of experimental conditions. As of 1933, the focus shifted and a national study was undertaken to measure and classify the intensity of soil erosion. During this phase, great importance was attached to the use of agricultural terracing to control erosion.

Still at the beginning of 1933, extensive government soil conservation programs were implemented on private land to create jobs for those left jobless by the Great Depression, in an effort to help protect and improve the land, following a Keynsian approach to economic policy.

Bennett (1933, 1939) convinced the Administration to adopt a policy of incentives for soil conservation. In 1935, Congress voted a bill that established soil conservation work on a permanent basis, founding the Soil Conservation Service (SCS). The 1935 act was very important in establishing soil conservation as national policy, serving as a model for many other countries, including Brazil. At the beginning of 1936, the American Supreme Court sanctioned the new Soil Conservation and Domestic Allotment Act that provided a framework for helping and subsidizing farmers who adopted the soil conservation program. This led to the dual nature of government conservation efforts that persists even today.

Bennett (1935, 1939, 1955) recognized the mutable character of the natural world, particularly in terms of the changes brought about by soil erosion. He helped create and apply new techniques for maintaining and increasing soil productivity. He also demonstrated, based on an analysis of erosion costs, that soil conservation was economically viable. As a researcher, his primary objective was to move away from the simple exploitation of the land purely for profit, towards the administration of a resource that belonged to the entire community and that individuals were merely granted a right to use. His efforts won him the title of "Father of Soil Conservation".

Baver (1951) also drew attention to the seriousness of the problems caused by soil erosion, demonstrating the importance of ongoing studies on erosion costs in an effort to establish an international data base on the total cost of these losses. For Baver, this was the most efficient way of convincing farmers and society of the importance of planned soil conservation.

Also in 1951, the Land Use Capability System was developed in the United States, based on proposals of Klingebiel and Montgomery (Klingebiel, 1958; Klingebiel & Montgomery, 1961). They thought it was important to investigate the location, extent and suitability of each soil type for different uses. This work was of fundamental importance for conserving the soil and understanding patterns of organization of agricultural space, as it was increasingly transformed by human activity and technological development. It also allowed the planning of forms of land use and occupation and the identification of effects of bad land use.

In 1965, based on the significant volume of information and research on the factors involved in the soil erosion process, Wischmeier and Smith developed the Universal Soil Loss Equation (USLE), a model for estimating soil losses caused by water erosion. Considered a landmark in the development of soil and water conservation, this model boosted research and stimulated soil erosion control in numerous parts of the world (Wischmeier & Smith, 1965, 1978).

In Brazil, concerns about controlling soil erosion date from the thirties, as a result of joint individual and institutional efforts in various parts of the country.

The Agronomic Institute in Campinas, São Paulo, led the way and is the most traditional and experienced Brazilian institution in this field. Since 1943, ongoing soil erosion studies have been carried out, always emphasizing the need to use conservation management methods. João Quintilliano de Avellar Marques was one of the pioneers of this institution.

Marques et al. (1961) were the first Brazilian researchers to associate soil erosion with economic issues, estimating the cost-benefit for soil use and the financial returns of conservation. Bertoni & Lombardi Neto (2008) also discussed the economic importance of soil conservation.

In the northeast of Brazil, Silva et al. (1985) documented the effects of soil erosion on yield, demonstrating the effects of soil conservation on farmers' expenditure and earnings.

The Paraná Agronomic Institute (IAPAR) was one of the pioneers in the "direct approach" to soil erosion costs. The studies were published in a book, "Controle da erosão no Paraná, Brasil: sistemas de cobertura do solo, plantio direto e preparo conservacionista do solo" *[Soil erosion control in Paraná, Brazil: systems of soil cover, no-tillage and conservationist soil preparation]* (Derpsch et al., 1991), and in a technical report, "Implicações econômicas da erosão do solo e do uso de algumas práticas conservacionistas no Paraná" *[Economic implications of soil erosion and the use of some conservation practices in Paraná]* (Sorrenson & Montoya, 1989), as well as in internal documentation.

Marques (1998) was a researcher at Embrapa Meio Ambiente (the environment unit of the Brazilian Agricultural Research Corporation). He used methods for costing the replacement of nutrients and "sacrificed production" to assess the effects of *on-site* and *off-site* soil erosion in the hydrographic basin Sapucaí, in the north of São Paulo state. The *off-site* costs generated by river sedimentation were estimated at around 10 million dollars a year, whereas *on-site* costs were around 6 million dollars a year. For Marques, the market system is flawed, since most of the cost of soil erosion is borne by society.

Rodrigues (2005) studied the costs of soil erosion by comparing no-tillage and conventional systems of soybean and maize in the Cerrado region. When used for producing soybean, the adoption of no-tillage raised production costs by 0.47 , but reduced soil erosion costs by 81.22 %. In no-tillage maize crops, production costs dropped by 5.92 % and soil erosion costs by 29.43 %. This was a concrete example of the social and economic benefits of agricultural conservation practices.

Bertol et al. (2007) studied the increased soil erosion costs resulting from losses of water, soil and nutrients in three management systems and various crops in the south of the Santa Catarina Plateau. Using no-tillage, the *on-site* costs of nutrient losses were around 15 dollars per hectare per year. With minimum tillage, the costs were a little more than 16 dollars while in conventional planting they reached almost 25 dollars. The study indicated that conservation management systems minimize the adverse economic effects of nutrient losses.

Sarcinelli et al. (2009) conducted a study on the costs and benefits of conservation practices in the micro-basin of the creek Oriçanguinha, in the state of São Paulo. The *on-site* costs of replacing nutrients in cultivated areas were estimated at around 28 to 73 dollars per hectare. This is equivalent to an average nutrient replacement cost of 50.49 dollars per hectare per year. The authors concluded that technical and economic incentives are necessary to encourage farmers to relinquish some of their short-term profitability in favor of greater medium- and long-term economic and ecological sustainability for their crop and livestock systems.

Research has progressed. There is no doubt that technical advances have been achieved in Brazilian agriculture in terms of controlling soil erosion through the adoption of conservation practices. However, there is still a long way to go, and this will involve ongoing and determined interdisciplinary discussion on research, development and innovation concerning soil degradation and the cost inflicted on the farmer and society in general.

LOSSES INDUCED BY SOIL EROSION

The process of erosion leads to the gradual destruction of the soil's properties (Zachar, 1982; Cassol & Lima, 2003; Bertoni & Lombardi Neto, 2008), since it not only carries away soil particles but also nutrients, organic matter and pesticides (Bronick & Lal, 2005; Bertol et al., 2007), preventing or retarding the normal plant development (Pierce et al., 1984; Osterman & Hicks, 1988; Christensen & Mcelyea, 1988; Montgomery, 2007).

Soil erosion is directly influenced by climate, soil type, topography, land use and management. Human influence on the environment through farming activities accelerates erosive action, causing great damage (Bennett, 1939; Zachar, 1982; Morgan, 2005). The accelerated erosion process occurs when the natural balance between soil loss and recovery is affected, with a variety of adverse effects, including economic losses (Bennett, 1929, 1933).

Soil loss by erosion tends to increase production costs in the medium and long term, with an increasing demand for liming and fertilizer applications and reduced operational efficiency of machines, incurring costs to control the situation (Uri, 2000; Bertoni & Lombardi Neto, 2008). This set of factors results in a drop in the soil's productive potential (Tenberg et al., 1998; Knowler, 2004), which eventually leads to a drop in the land value (Ervin & Mill, 1985; Fletcher, 1985; Hertzler et al., 1985; Palmquist & Danielson, 1989).

Soil erosion has adverse effects both on and off production sites (Chart 1), which have economic consequences that are important to farmers and society (Bennett, 1935; Pimentel et al., 1995; Uri, 1999, 2000, 2001).

Chart 1. On-site and off-site losses caused by soil erosion

On-site
Soil loss
Nutrient loss
Loss of organic matter
Drop in the soil's chemical, physical and biological fertility
Damage to plantations and improvements
Yield drop
Production loss
Shrinkage of the available planting area
Sales reduction
Off-site
Sedimentation
Sedimentation of lakes and rivers
Drop in the capacity of water bodies to receive water
Flooding
Overflows
Flash floods
Landslides
Destruction of roads, railways, waterways and other public assets
Obstruction of waterways navigable
Eutrophication
Loss of biodiversity
Impaired water quality
Adverse effects on water treatment
Adverse effects on electrical energy generation
Drop in food supply
Inflated food prices
Restriction on recreational activities in water bodies

Source: prepared from Clark (1985), Pimentel et al. (1995), Uri (2001) and Crosson (2007).

On-site effects directly affect cultivable land, mainly through the loss, destruction or reduction of organic matter and nutrients. They also lead to a drop in cultivable soil depth and moisture available for plants. As a result, a limitation is imposed on what can and cannot be grown, and costs also rise in terms of expenditure on fertilizer to maintain productivity (Colacicco et al., 1989; Morgan, 2005). The knock-on effect of these difficulties are instability in food production, price rises for commodity derivatives (Baver, 1951; Fletcher, 1985), land devaluation and even abandonment of the land (Fletcher, 1985; Palmquist & Danielson, 1989; Tegtmeier & Duffy, 2004). The drop in land value can, in turn, cause a generalized drop in property values (Ervin & Mill, 1985). In addition, there are other impacts linked to production, such as additional costs for irrigation, replanting costs, loss of investments in improved production systems that become inefficient in soils with accelerated erosion, and labor costs to repair the damage caused by soil erosion. Moreover, those people who earn a living in rural activities become gradually poorer as a result of continuous soil erosion.

In areas where soil erosion limits or inhibits production, farm work ceases to be worth the effort and investment, causing agricultural workers and their families to migrate to urban centers. This results in an oversupply of labor force which, in many cases, is unprepared for any work other than agricultural, generating slum areas (Santos, 2005) and which needs government assistance to be able to survive. In the end, the result is nothing less than social and economic disorganization.

Off-site effects are mainly the result of sedimentation, reducing the capacity of rivers and drainage ditches, increasing the risk of flooding, blocking irrigation channels and shortening the useful lives of reservoirs (Forster et al., 1987; Robertson & Colletti, 1994; Pimentel et al., 1995; Uri, 2001). Many hydroelectric power plants and irrigation projects have been abandoned as a result of erosion (Crowder, 1987; Colaccico et al., 1989). In addition, sediments contain chemicals that can pollute waterways, increasing nitrogen and phosphorus levels in water bodies, causing eutrophication, increasing the cost of electricity generation and water capture for supplying urban centers and causing a shortage of water resources for irrigation-dependent regions (Pimentel & Kounang, 1998). A further consequence of soil degradation is the release of CO_2 into the atmosphere (Lal, 2007; Salvati & Zitti, 2009). The costs of all these effects can also be quantified.

THE COSTS OF SOIL EROSION

Cost estimates for soil erosion have been produced in various parts of the world since the beginning of the 20th century (see Table 1).

The first estimates of soil erosion costs were made by Bennett (1933) in the United States. He expressed concern about the consequences of soil erosion in the US and used information on soil erosion costs to alert farmers, society and the government for the need and importance of adopting conservation practices. He succeeded in convincing the nation to declare soil erosion a national threat.

Bennett's studies initially involved surveying soil losses in terms of the drop in organic matter, nutrients and productivity. He used an approximation of the cost of replacing nutrients with commercial fertilizer equivalents to estimate erosion costs. His calculations represented the amount of fertilizer farmers would need to apply to crops in order to offset the nutrient losses due to erosion.

The scientific methods he used were not designed to meet present day standards, since his work had a more political and legislative connotation. Perhaps this is why his pioneer work on soil erosion costs did not attract much attention in academic circles. This type of study became almost exclusively the prerogative of the US Soil Conservation Service until the mid-sixties. However, Bennett developed a series of concepts related to the on- and off-site costs generated by the erosion process.

Advances in estimating soil erosion costs were made after the development of the Land Use Capability System (Klingebiel, 1958; Klingebiel & Montgomery, 1961) and the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1965, 1978).

Most studies in Table 1 made use of the USLE to calculate soil losses and then measure other damage caused by erosion. They established the cost per ton of lost soil, assigning it a value based on organic matter and nutrient losses. Some authors calculated N and P losses (Stocking, 1988; Colacicco et al., 1989). Others also included K (Marques et al., 1961; Larson et al., 1983; Crosson, 1986; Troeh et al., 1991; Pimentel et al., 1995; Hein, 2007; Montanarella, 2007) and others, Mg and Ca (Sorrenson & Montoya, 1989; Martin et al., 1991; Marques, 1998; Rodrigues, 2005; Bertol et al., 2007; Sarcianelli et al., 2009).

Costs were assessed on different geographical scales. Some of the most extensive studies are generalized and provide estimates for economic blocks and countries. In these studies, the authors normally used secondary data on soil, nutrient and yield losses to determine the average cost of erosion per hectare and, once these data were obtained, they extrapolated to the entire cultivable area of a given region (Bennett, 1933; Larson et al, 1983; Crosson, 1986; Stocking, 1986, 1988; Bishop & Allen, 1989; Colacicco et al., 1989; Troeh et al., 1991; Margulis, 1992; Bojö & Cassells, 1995; Pimentel et al., 1995; Pretty et al., 2000; Uri, 2000; Riksen & Graaff, 2001; Hansen et al., 2002; Cohen et al., 2006; Montanarella, 2007; Kuhlman et al., 2010). A significant limitation of these studies is that they often omit the regional

Table 1. Estimates of soil erosion costs in dollars per year

Reference	Location	Estimate (dollars/year)	Costs	Measured losses
Bennett, 1933	USA	400.10^6	on-site	Nutrients and Soil (3 billion t $year^{-1}$)
Marques et al., 1961	Brazil, São Paulo	27 to $1.5.10^3$ (1)	on-site	Nutrients (N, P and K), Productivity and Soil (0.9 to 26.6 t ha^{-1} $year^{-1}$)
Larson et al., 1983	USA	500.10^6 to 1.10^9	on-site	Organic matter and Nutrients (N, P and K)
Hitzhusen et al., 1984	USA	1.10^9 to 3.10^9	off-site	Drainage and Water treatment
Clark, 1985	USA	1.10^9 to 13.10^9	off-site	Sediments
Huszar & Piper, 1986	USA, New México	466.10^6	off-site	Soil (6 to 100 t ha^{-1} $year^{-1}$)
Crosson, 1986	USA	$1.7.10^9$ to $1.8.10^9$	on-site	Nutrients, Productivity and Erosion control
Stocking, 1986	Zimbabwe	117.10^6	on-site	Soil (50 t ha^{-1} $year^{-1}$)
Crowder, 1987	USA	597.10^6 to 819.10^6	off-site	Sediments
Moore & McCarl, 1987	USA, Willamette Valley	55.10^3	off-site	Sediments
Stocking, 1988	Zimbabwe	$1.5.10^9$	on-site	Nutrients (N and P)
Bishop & Allen, 1989	Mali	29.10^3 to 112.10^3	on-site	Soil (6.5 t ha^{-1} $year^{-1}$)
Colacicco et al., 1989	USA	5.10^6 to $1.2.10^9$	on-site	Organic matter, Nutrients (N and P), Productivity and Soil (3.2 to 12.9 million t ha^{-1} $year^{-1}$)
Magrath & Arens, 1989	Indonesia, Java	340.10^6 to 406.10^6	on-site	Productivity
Ribaudo et al., 1989	USA	7.10^9	off-site	Water storage and distribution, Flooding Irrigation, Navigation, Commercial fishing, Recreation and Water treatment
Sorrenson & Montoya, 1989	Brazil, Paraná	242.10^6 to 30.10^9	on-site	Nutrients (N, P, K, Ca and Mg) and Soil (20 t ha^{-1} $year^{-1}$)
Martin et al., 1991	Brazil, São Paulo	212.10^6	on-site	Nutrients (N, P, K, Ca and Mg)
Troeh et al., 1991	USA	20.10^9	on-site	Nutrients (N, P and K)
Margulis, 1992	México	500.10^3	on-site	Productivity (corn, soya and wheat) and Soil (10 to 15 t ha^{-1} $year^{-1}$)
Bojö & Cassells, 1995	Ethiopia	130.10^6	on-site	Soil (42 t ha^{-1} $year^{-1}$)
Pimentel et al., 1995	USA	44.10^9	on-site and off-site	Water, Organic matter, Nutrients (N, K and P), Productivity, Soil (17 t ha^{-1} $year^{-1}$) and Sediments
Steiner et al., 1995	USA	120.10^3 to 330.10^3	off-site	Sediments
Marques, 1998	Brazil, São Paulo	$5.4.\ 10^6$ to $9.9.10^6$	on-site and off-site	Nutrients (N, P, K, Ca and Mg) Soil (9.6 t ha^{-1} $year^{-1}$) and Sediments
Pretty et al., 2000	UK	156.10^6	on-site and off-site	Organic matter and CO_2 (1.42 t C ha^{-1} $year^{-1}$), and Sediments
Uri, 2000	USA	$37.6.10^9$	off-site	Sediments (5.5 t ha^{-1} $year^{-1}$)
Hansen et al., 2002	USA	5 (2)	off-site	Navigation
Riksen & Graaff, 2001	EU (4 members)	60.36 (1)	on-site	Productivity (sugar beet and rape)
Tegtmeier & Duffy, 2004	USA	$2.2.10^9$ to $13.3.10^9$	off-site	Sediments (958 million t $year^{-1}$)
Rodrigues, 2005	Brazil, Goiás	38.39 to 165.73(1)	on-site and off-site	Nutrients (N, P, K, Ca and Mg), Productivity (corn and soya), Soil (1.1 to 4.4 t ha^{-1} $year^{-1}$) and Sediments
Cohen et al., 2006	Kenya	390.10^6	on-site and off-site	Macroeconomic
Montanarella, 2007	EU (25 members)	$45.4.10^9$	on-site and off-site	Organic matter, Nutrients, Soil (0.5 to 10 t ha^{-1} $year^{-1}$) and Sediments
Bertol et al., 2007	Brazil, Santa Catarina	14.83 to 24.94(1)	on-site	Nutrients (N, P, K, Ca and Mg) and Soil (1.04 to 8.9 t ha^{-1} $year^{-1}$)
Hein, 2007	Spain, Puentes	5.12 to 66.54(1)	on-site	Nutrients (N, P and K) and Soil (7.1 to 206.9 t ha^{-1} $year^{-1}$)
Sarcinelli et al., 2009	Brazil, São Paulo	28.32 to 72.65(1)	on-site	Nutrients (N, P, K, Ca and Mg)
Kuhlman et al., 2010	EU (25 members)	165.85 to 409.10(1)	on-site	Soil (0.5 t to 10 t ha^{-1} $year^{-1}$)

(1) Per hectare. (2) Per ton of eroded soil. All soil erosion cost estimates were converted into US dollars, based on the exchange rate at the time of each study.

features of a geographic area, such as different soil types. For this reason, they are less accurate in methodological terms, despite their impressive scope.

Other researchers worked within state or municipal boundaries, and mainly in hydrographic basins (Marques et al., 1961; Huszar & Piper, 1986; Moore & McCarl, 1987; Magrath & Arens, 1989; Sorrenson & Montoya, 1989; Martin et al., 1991; Marques, 1998; Rodrigues, 2005; Bertol et al., 2007; Hein, 2007; Sarcinelli et al., 2009). Their studies are more accurate in methodological terms and take account of all USLE factors.

Another procedure for calculating erosion costs is based on yield losses in commodities of major economic importance in a given region, such as coffee, sugarcane, maize, soybean, and wheat. Yield loss rates obtained by regression are used by the authors to calculate costs based on the income the producer no longer receives (Marques et al., 1961; Crosson, 1986; Colacicco et al., 1989; Magrath & Arens, 1989; Margulis, 1992; Pimentel et al., 1995; Riksen & Graaff, 2001; Rodrigues, 2005). However, yield losses cannot be attributed solely to erosion, but other variables are involved as well.

Crosson (1995), Pimentel & Kounang (1998) and Pimentel et al. (1999) also point to biological losses observed in the soil, which are costs associated with the erosion process. Although the measurement of biological losses is incipient and the figures are only approximate, they need to be taken into account in any attempt to assess the total costs of soil erosion.

Finally, in many studies, an attempt was made to present soil erosion costs taking the effects of the adoption of conservation practices in different production systems into consideration, to show that in addition to minimizing the effects of the erosion process, they are economically viable and profitable (Uri & Lewis, 1998; Rodrigues, 2005; Bertol et al., 2007; Hein, 2007; Kuhlman et al., 2010).

To summarize, the on-site costs were estimated on the basis of the loss of soil, nutrients, organic matter, productivity and yield.

Off-site costs were estimated in various ways. However, the main off-site effects are linked to sedimentation (Clark, 1985; Huszar & Piper, 1986; Crowder, 1987; Pimentel et al., 1995; Steiner et al., 1995; Montanarella, 2007), determined using the USLE and based on the amount of sediment reaching water bodies and which, for instance, can affect hydroelectric power plants and water treatment stations. The costs incurred by this process were estimated in terms of increased expenditure on electrical energy generation (Marques, 1998) and water treatment (Hitzhusen et al., 1984). Off-site costs can also be estimated based on the operational costs of dredging waterways (Hitzhusen et al., 1984; Marques, 1998), since sedimentation can adversely affect irrigation, navigation, recreation and water storage and distribution (Ribaudo et al., 1989; Hansen et al., 2002), in addition to causing flood damage, the costs of which are reflected in the expense of repairs. Off-site costs can also be determined based on price rises for agricultural commodities, resulting in macroeconomic instabilities (Alfsen et al., 1996; Cohen et al., 2006).

Depending on the methods used to estimate on- and off-site soil erosion costs, the results can be extremely variable (Table 1). The majority of studies estimate on-site costs, and these studies show an even wider fluctuation in the estimated figures. Moreover, in terms of the breakdown of total erosion costs, off-site costs are higher than on-site costs. For instance, in the United States the annual soil erosion on- and off-site costs were estimated at 44 billion dollars a year. However, when we look at on-site costs alone, the figures vary between 5 and 20 billion dollars, but the variation for off-site costs is between 55 thousand and 37 billion dollars a year.

Among the Brazilian studies, Marques et al. (1961) estimated costs for the state of São Paulo at between 27 and 1,500 dollars/hectare/year, with soil losses of 0.9 to 26.6 t ha^{-1} $year^{-1}$, and the study by Bertol et al (2007) estimated the costs for the state of Santa Catarina at between 14.83 and 24.94 dollars/hectare/year as a result of soil losses of 1.04 to 8.9 t ha^{-1} $year^{-1}$. For an average loss of 20 t ha^{-1} $year^{-1}$ from 6 million hectares of annual crops in 1984 in the state of Paraná, Sorrenson & Montoya (1989) estimated the minimum cost at 242 million dollars a year in terms of nutrient runoff through soil erosion, and Martin et al. (1991) in São Paulo state calculated costs of 212 million dollars for fertilizers replacing lost nutrients.

Operationalization of on-site costs consists of aggregating the expense incurred in repairs of the adverse effects of any disruption in production, and off-site costs are operationalized mainly in terms of damage repair.

Erosion costs do not depend solely on the physical quantity of soil loss. They are also dependent on the economic repercussions of these losses. The physical erosion data gives some idea of the impact of erosion on quality, but is not sufficient to indicate the economic scale of its impacts. The main aim is to establish figures for the amount of losses.

This scenario draws attention to the urgent need to prevent and control soil degradation processes. For this purpose, data on erosion costs are of fundamental importance, especially in developing countries, which are usually more economically dependent on farming.

FINAL CONSIDERATIONS

In addition to physical, chemical and biological losses, soil erosion causes economic losses which can be expressed in terms of the costs incurred by farmers and society to repair the damage arising from this process.

In the United States, soil erosion costs have been estimated at 44 billion dollars a year and in Brazil, in Paraná state alone, they amount to some 242 million dollars a year. The estimated costs of soil erosion vary from the 5 dollars spent to remove each ton of sediment to keep navigation activities in operation, to 45.4 billion dollars a year in the European Union, spent to offset the effects brought about by the loss of soil fertility and sedimentation of water resources.

This gives some idea of the importance of conservation management techniques designed to minimize soil degradation, reduce the erosion effects and also to make it possible, in the medium and short term, to mitigate on- and off-site costs. Therefore, in addition to being in the public and private interest, these land management systems are in line with the principles of sustainable agriculture.

Estimating erosion costs helps economic agencies in decision-making on soil conservation policy and provides governments with tangible evidence of the need to implement public policies aimed at ensuring the sustainable development of economic activities linked to the farming sector.

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