Potential Use of Polyacrylamide for Soil Erosion Control in Brazil

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Abstract

Since soil erosion is currently a worldwide threat, its control has become a necessity. The performance and effectiveness of synthetic organic polymers such polyacrylamide (PAM), have been intensively studied, especially for erosion control in temperate climate conditions. In tropical regions, however, where climatic conditions are usually severe, very little research has been conducted. The Brazilian region is a good example, where few papers on this subject exist. In addition to the severe climatic conditions, careless land use has been prevalent for many years. The use of PAM for erosion control in Brazilian soils may be a good option to minimize the impacts of the soil degradation process, but more research is required to optimize its application.

Keywords: Soil erosion control, Brazilian soils, Polyacrylamide

1. Introduction

Soils constitute a key resource for the production of food, feed, fiber, and fuels, and they also play a central role in determining the quality of our environment. Soils differ in their properties — their resource endowment or natural capital, the rate of soil processes, and the ecosystem services they provide, as well as in their vulnerability and resilience to degradation (Palm et al., 2007).

Soil degradation is a cyclical and biophysical process exacerbated by socio-economic and political factors. Physical soil processes involve a decline in soil structure, leading to an increase in bulk density, decrease in total and macroporosity, reduction in infiltration, increase in runoff, and exacerbation of erosion by water and wind (Lal, 2001).

According to a data base presented by Nam et al. (2003), South America is the continent that presents the largest annual soil loss rates (16.7 t ha^{-1} y^{-1}, compared to the world average of 11.5 t ha^{-1} y^{-1}). Brazil also suffers high soil loss rates. One reason for this is that land use and tillage systems in Brazil are far from sustainable.

Various polymers and biopolymers have long been recognized as viable soil conditioners, because they stabilize soil surface structures and improve pore continuity (Orts et al., 2008). An example is the application of soil amendments, including gypsiferous materials and anionic polyacrylamide (Cochrane et al., 2005).

The aim of this paper is to discuss some points of interests for application of polyacrylamide to Brazilian soils. We also intend to stimulate the development of research in Brazil regarding this subject and the optimization of the use of this product in Brazil.

2. Soil erosion

In erosion, the breakdown of soil particles on the surface results from the impact energy of raindrops and the shear strength of surface runoff. The most severe effect is due to loss of topsoil depth in soils with a root-restrictive layer (Lal, 2001). On the other hand, soil erosion is considered to have the greatest impact among surface hydrological processes (van Lier et al., 2005).

Boardman (2006) comments on "big questions" concerning the temporal and spatial context of erosion, the reasons for its occurrence, its impact, and the responses (actual and potential) of individuals and society (Table 1). Two important questions, however, are perhaps missing from this set: (1) What is the currently available technology for solving the specific problems at a given place? And (2) Is this technology (if it exists) available for implementation (Has the technology transfer been successful?).

Among the currently existing technologies, there are various different types of erosion control methods (LLRB, 2003):

(1) Minimize both the area and time that soil is exposed.

(2) Manage storm water moving across a site by reducing its velocity and volume.

(3) Install erosion and sediment control measures early in construction. Keep them well maintained.

(4) Keep sediment on site.

(5) Promote seeding in the project area (which can reduce erosion by 90%).

(6) Maximize the establishment of vegetation by selecting the appropriate seed, knowing and preparing the soil, preparing the seedbed, and planting at the right time.

There are methods appropriate for farming crops and urban landscaping sites, including erosion control of unpaved roads (Lal, 2001). Residue management and reduced tillage as conservation practices have not been readily adopted in agriculture (irrigated by rain). Owing to high residues on the soil surface produced by such practices, the water flow and sometimes planting and harvesting operations are impeded. Also, for following crops such as potato, dry bean, and sugar beet, very little residue is left to protect the soil surface from erosion (Sepaskhah and Bazrafshan-Jahromi, 2006).

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3. Land cover and erosion occurrence along Brazilian territory.

Brazil is the fifth largest country worldwide. It has widely varying climates (INMET, 2010), soils (Bernoux et al., 2002), land uses and covers (IBGE, 2006); in many parts the topography is hilly.

The soils in Brazilian territory have been used for many purposes for over five centuries but principally during the 20th century the erosion process became an important threat (Brannstrom and Oliveira, 2000). According to an IBGE census (2006), in 2006 there were almost 3.3 million km^2 occupied by some kind of agricultural activity (crop or animal production); the predominant one being pasture (approximately 50%).

It is difficult obtain data for soil loss rates for the Brazilian territory as a whole. A database for some regions, however, is available. For instance: Bertolini and Lombardi Neto (1993) show a table of the annual average value for São Paulo State (Table 2).

Table 2 shows that unpaved roads are far the highest threat regarding accelerated erosion, followed by annual and temporary crops. Owing to an increase in the rate of soil erosion that occurs with land-disturbing activities (Buol, 1995; Hayes et al., 2005), construction sites are a primary source of sediment.

For other regions, Beskow et al. (2009) estimated, using GIS technology, the annual soil loss rate for a part of a river basin located in Minas Gerais State (Rio Grande River Basin – studied area 6,273 km^2). The results showed that the major area of the basin (about 53%) had an average annual soil loss of less than 5 t ha^{-1} y^{-1} and soil losses exceeded the presumed tolerable limits over approximately half of the area. Andrello et al. (2003) studied soil loss in a watershed located in Paraná State (Southern Brazil) and found a average annual soil loss of 15.8 t ha^{-1} y^{-1} for annual crops, 13.9 t ha^{-1} y^{-1} for pasture and 5.48 t ha^{-1} y^{-1} for coffee (the method used was Cesium-137).

Soil erosion is a natural process, occurring over geological time (typically at rates of 0.1 - 5 t.ha^{-1}.y^{-1}) (Kirkby, 2001). Erosion literature commonly identifies acceptable rates of soil erosion (Sparovek and Schung, 2001), but these rates usually exceed the rates that can be balanced by weathering of new soil from parent materials. Taking a long term view, human-induced erosion should not exceed the rate of weathering, which converts bedrock or other parent materials into a fine-textured regolith. On this view, almost any form of cultivation on sloping land will increase erosion above the acceptable natural level, so that this point of view can only realistically be applied where the soils are already very shallow. An alternative is based on the time required to replace the topsoil, defined by the USDA-NRCS as the *tolerable soil loss.* This is the annual rate of soil erosion that, if exceeded, would remove soil from the landscape faster that organic matter is being incorporated to regenerate the topsoil (Kirkby, 2001).

A strong effort is required to diminish the soil loss in Brazil. Al-Kaisi et al (2003) mention conservation and best management practices:

(1) - *Crop rotations*: Extended crop rotation and permanent cover crops effectively protect the soil from the impact of raindrops. The thick, fibrous root systems associated with cover crops also bind the soil particles together.

(2) - *Residue management*: Plant residue controls soil erosion by intercepting raindrops, blocking wind erosion, reducing surface water runoff, and preventing soil detachment. When using a combination of conservation tillage practices and surface residue management, it is critical to maintain the highest possible amount of residue cover.

(3) - *Tillage practices*: Whether using no-till, conservation tillage, or conventional tillage systems, harvest is the best time to begin the next year's residue management. For effective soil erosion control, try to maintain a residue cover of 30 percent or more during the off-season and at planting time.

(4) - *Grassed waterways*: Wide, shallow, sod-lined waterways reduce the speed of water by providing a grass cushion and preventing gully formation. They also act as a filter by trapping sediment and protecting covered soil from being detached and transported.

(5) – *Terraces*: Terraces break up slope lengths and reduce steepness, thus diminishing surface flow and sediment transport. They are easily adapted to the producers' needs, soil type, and equipment.

(6) - *Conservation buffers*: Buffers (areas or strips of land in which permanent vegetation is established near row crops) are designed to intercept sediment flow and protect the soil from detachment.

(7) - *Contour farming*: Planting rows on the contour helps to channel small runoff streams across, rather than down, the slope and creates a speed bump for larger flows.

All of these conservation practices can be used in Brazilian territory (including urban settlements and mines) according to soil type, climate, and the kind of crop and tillage system (Silva et al., 2007). But, it seems that in some cases these options are not fully adequate. In cases such as unpaved roads, dry regions, crops that generate small amounts of mulch, a complementary product should be used. Owing to its chemical characteristics, such a product can act as a soil erosion controller, retaining water and aggregating soil particles.

4. Polyacrylamide (PAM) and its potential use in erosion control.

Hydrogel polymer is the name given to long molecule chains constituted of repeating units that capture water molecules. This characteristic makes them excellent at soaking up water.

A synthetic organic polymer derived from petroleum, PAM, is an industrial flocculent used worldwide in several industries (Lentz, 2008). It is a water-soluble, very long chain, high molecular weight organic polymer produced from natural gas, with characteristics which make it useful as a soil amendment to control runoff and soil loss (Flanagan et al., 2002).

PAM was initially used to reduce erosion in irrigated agricultural fields and is also being used nowadays to reduce erosion from highway embankments, landfill caps, and other areas that need to have stable surfaces while vegetation is being established (Flanagan et al., 2003).

The versatility of PAM is one of the aspects that make it attractive. As shown in Figure 1, PAM can be used to control surface sealing and crusting, increase seedling emergence, reduce runoff erosion, as well as reduce fertilizer and pesticide losses. In irrigation systems, after planting, PAM is sprayed on the soil either using a sprinkler irrigation system or via a high-pressure sprayer (Green and Stott, 2001).

The polymer can be applied directly through irrigation water or indirectly as dry powder or granules placed on the soil surface and activated by irrigation or rain (Sojka et al., 2007).

The way in which the polymer adsorbs to the soil is the key to its effectiveness as a soil amendment (Green et al., 2000). It forms bridges to soil particles through cations or anions in soil solution (Cochrane et al., 2005). Figure 2, a micrograph obtained from Ross et al. (2003), illustrates the glue-like porous appearance of soil with PAM, and the poor visual micro-aggregation in the untreated soil.

Soil characteristics play a crucial role in the comprehension of the process of adsorption of PAM. The surface chemistry of soils and the large physical-chemical domain of PAM macromolecules make them useful compounds for management of soil processes governed by flocculation, aggregation, and structure stabilization.

In the absence of divalent cations (Green & Stott, 2001), however, PAM is ineffective. For PAM to work effectively there must be a source of divalent cations (Green et al., 2000). The divalent cation source may be in the PAM solution, in the soil, or applied directly to the soil (i.e. gypsum application).

Anionic PAM acts as a film covering the soil particles and aggregates. It also acts as bridge to the outside of charged particles by using a cationic source for constitution of the bridge. The effect of gypsum added to the PAM application enhances adsorption when gypsum is applied before or at the same time as PAM, because the gypsum supplies a cationic source to create bridges with clay particles. Application of gypsum after PAM results in an additive effect of the amendments (Wallace et al., 2001).

Although PAM application to soil or irrigation water in some cases may reduce active bacterial and fungal biomass, it does not seem to appreciably affect the soil microbial metabolic potential (Sojka et al., 2006).

In this context we can observe that the use of such technology seems to be promising, but is neither well developed nor widely disseminated in Brazil.

5. The use of PAM in erosion control in Brazil.

There are currently few data in the scientific literature concerning appropriate rates of PAM addition as a function of slope, soil type, ground cover, weather, or other factors for tropical soils, especially in South America. For Brazilian territory, Wallace et al. (2001) and Cochrane et al. (2005) carried out experiments in subtropical soils, and Pellegrini et al. (2002) and Melo et al. (2009) for tropical soils.

Wallace et al. (2001), using a programmable rainfall simulator, studied the performance of PAM for subtropical soils located in Rio Grande do Sul state and verified that all amendments decreased runoff and protected the soil surface against erosion. Gypsiferous materials increased the electrolyte concentration of the soil surface and flocculated the clays to prevent erosion. PAM effectively conserved the topsoil by covering the soil like a film.

The authors also observed that adsorption of PAM constituted an important factor for understanding the conditions under which it benefits the soil. This low activity and acidic soil is affected differently when PAM is applied to dry soil compared to the pre-wetted plots, with different levels of moisture. Steady-state values of the soil were similar for all treatments, proving them to be useful for preventing soil loss. Additionally, the surface pore space values showed the benefits of using gypsum and PAM with the amended soils, producing a greater porous space than the bare untreated soil.

In a study carried out by Cochrane et al. (2005), the authors verified the effectiveness of the soil amendments in conserving topsoil by preventing water-induced erosion in a Brazilian sandy Alfisol soil (coarse-loamy, mixed, thermic Typic Paleudalf). A programmable rainfall simulator was also used at the experimental station located in Rio Grande do Sul State, in a newly harvested black oat field that was moldboard plowed and disked twice. Plots were on bare tilled soil with 8% to 12% slope. The soil treatments consisted of a single 5 Mg ha^{-1} surface application of phosphogypsum (PG) byproduct, a single 20 kg ha^{-1} surface application of anionic polyacrylamide (PAM), a combined amendment (PAM+PG) with the same rates as above, and an untreated soil (control).

Simulated rainfall average rainfall intensity was 25 mm h^{-1} for 2 h. Sediment and runoff samples were collected at intervals during the experiment, and soil surface samples inside the plot were taken after the rain for surface crusting analysis. The total soil loss shows that all the treated soils had less soil loss compared to the control (Figure 3). PAM and PAM+PG had steady-state runoff rates significantly smaller than that of the control. Hence, using amendments to reduce precipitation-induced erosion is a possible alternative conservation practice in this region of the world.

In another study, Pellegrini et al., (2002) studied the influence of gypsum and polyacrylamide in interrill erosion under simulated rainfall in a Vertisol (a typical soil class occurring in Brazilian semi arid regions, presenting high clay levels and with a relatively high yield crop when irrigated). The authors used experimental plots of 15% slope and simulated rainfall of 80 mm h^{-1} and PAM was applied one day before to allow drying (the rate of application was 300 ppm – 20 kg ha^{-1}).

Figure 4 shows the main results. The combination PAM + Gypsum presented the best result, with a reduction rate of almost 50%. The application of gypsum without PAM presented a result little better than PAM without gypsum.

Melo et al. (2009) studied the aggregate stability of a Fluvent Soil located in a semi-arid region of Pernambuco State (Brazil). Samples of aggregates from two situations were collected and separated into similar sizes (using 4.00 and 3.75 mm sieves): (1) soil impacted by salinization and (2) soil not impacted by salinization. After separation and drying, some aggregates were dampened with water and others were dampened with water containing polyacrylamide (0.001%). The aggregates were agitated in a vertical shaker. The presence of PAM altered the ponderated average diameter of the aggregates, both for salinized and non-salinized soils (Table 3). The authors also mention that after sieving, the highest aggregated stability was for the range 4.00 and 2.00 mm, where the greatest presence of aggregates retained in sieve of 2.00 mm mesh was also observed, indicating the notable influence of PAM.

In tropical environments, pluvial water, organic matter and applied fertilizers can cause significant changes in soil pH conditions. These changes can affect the ability of polymers to be adsorbed onto soils. This factor is compounded since, unlike in temperate zones where clayey soils usually have same grain size regime, tropical soils are dominated by minerals of constant surface potential, rather than constant surface charge (Galvão et al., 2007). Hence, owing to our lack of data, questions remain open concerning the effectiveness of the PAM in erosion control in tropical soils.

5.1 Threats where PAM might be successfully used (research needs) to avoid soil erosion:

PAM may be used in soils whose cover (any kind of vegetation) has been recently burned. In Brazil the "technique" of *slash and burn* is still used, both in regions covered with natural forest vegetation such as the Amazon and Atlantic Forest, as well as for some kinds of crop, such as sugarcane. As described by many authors cited by Are et al. (2009), burning had been identified as one of the main soil degrading practices that result in structural degradation of the soil. The excessive dependence on slash and burn, however, for land clearing by many farmers is explicable. Its beneficial effects include clearing bush debris and reducing weed infestation that would otherwise compete with crops for sunlight, water and soil nutrients. The ash deposits produced by burning help to fertilize the soil. This occurs via the immediate release of the occluded mineral nutrients—Mg, Ca, available P, for crop use. Moreover, increased soil temperatures produced by burning stimulate biological activity, and increase the mineralization of organic matter, thereby enhancing nutrient availability.

Most roadways and construction sites in developing countries, including Brazil, are not surfaced (see Figure 5 for an example). Thus, considerable amounts of lateritic clay and silt are removed by wind and vehicular action and entrained in the atmosphere as dust. In urban areas, soils are frequently contaminated. Excessive exposure to contaminated dust can cause human health problems (Galvão et al., 2007). Therefore, in some cases, the application of PAM, jointly with gypsum or another organic product, is a good option to diminish soil loss rates in some regions. Although few studies have yet been concluded, it seems that rates of PAM addition suitable for the steep slopes often found on construction sites will need to be much higher than the current recommendations or restrictions which are being established (Hayes et al., 2005).

In arid land, polymers could be the only viable way to limit soil loss (Abu-Zreig, 2006). The Northwestern region is an example, where the low availability of drinking water is another current problem.

6. Final considerations

The advances of PAM-based agricultural and environmental management technologies since the early 1990s have generally been rapid and great (Sojka et al., 2007), but not in Brazil. The use of PAM for erosion control in tropical soils indeed seems be a good option, but questions need be answered to allow its use. For example, the period of effectiveness of PAM after its application, depending on regional climate and chemical soil characteristics, is a crucial factor to be studied.

Another factor deserving special attention is the potential (or not) for the recuperation of degraded soils. Sojka et al. (2007), for example, do not mention the use of PAM for activities of soil recuperation. PAM is a product that should be used in severely degraded soils to retain clay, organic matter particles and other important materials that give fertility to the soil and conditions for vegetal life. Thus, it could be used as an indirect tool to restore the ecological conditions of degraded soils.

Experiments carried out using experimental plots under natural climatic conditions, especially sun exposure, wind, and rainfall, are essential for a better understanding the performance of PAM at high temperatures and in dry soils (studying, for example, the rate of degradation and the temporal decrease in effectiveness).

Finally, we agree with Sojka et al. (2007), that coupled with the ingenuity and creativity of soil and water researchers, PAM, related synthetic polymers, and potential future biopolymers hold significant potential for affordable environmental protection and improved efficiencies and economies of environmental, agricultural, and industrial processes dependent on the management of soil structure, water behavior, and control of suspended solids. Technology transfer, however, is also important. In other words: introducing and providing access to technology to farmers is as or more important as developing new technologies and products.

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Table 1. The big questions and issues.

Question	***Issues***
Where is the erosion happening? - Global hotspots	Scale Datasets
Why is happening? -The big picture: socio-economic drivers - The details: runoff, wind, soil, etc.	Causality
When it is happening? - Change through time, seasonality, climate	Temporality
Who is to blame? - Farmers driven by policy imperatives at national and local scales	Responsibility
How serious is it? - Magnitude, frequency	Impacts Economics
Who does it affect? - On and off-site impacts	Impacts
What does it cost? - Short and long term costs - Agricultural externalities	Economics
Over what time scale is degradation occurring? - Threat to agriculture and livelihoods	Sustainability
Can we do anything about it? - Effectiveness of conservation	Response
Who should take action? - Farmers; local, national government	Responsibility
Is the action worthwhile?	Ethics and economics
What is the risk of erosion in the future? - Land use or climate change or both	Prediction
Where is that risk? - Vulnerable soils, vulnerable communities	Scale

Source: Boardman (2006).

Table 2. Soil loss associated according to land use for São Paulo State (Brazil):

Land use	**Average Soil loss ($t.ha^{-1}.y^{-1}$)**
Annual crops	
Cotton	26.7
Peanuts	25.1
Rice	38.1
Bean	12.0
Corn	20.1
Other	24.5
Temporary crops	
Sugar-cane	12.4
Castor	41.5
Cassava	33.9
Permanent crops	
Banana	0.9
Coffee	0.9
Orange	0.9
Other	0.9
Other land use classes	
Pasture	0.4
Natural forest	0.4
Reforestation	0.9
Critical land uses (unpaved roads and peri-urban areas)	175.0
Other	1.0

Source: Bertolini and Lombardi Neto (1993).

Table 3. Ponderated average diameter (mm) of salinized and non-salinized soils at the three evaluated depths.

Soil	Ponderated Average Diameter (mm)	
	Without PAM	With PAM
Non salt (0 – 10 depth)	0.39	2.58
Non salt (10 – 20 depth)	0.28	2.72
Non salt (20 – 30 depth)	0.26	2.27
Salt (0 – 10 depth)	1.66	5.58
Salt (10 – 20 depth)	1.39	5.34
Salt (20 – 30 depth)	0.18	1.65

Source: Melo et al. (2009).

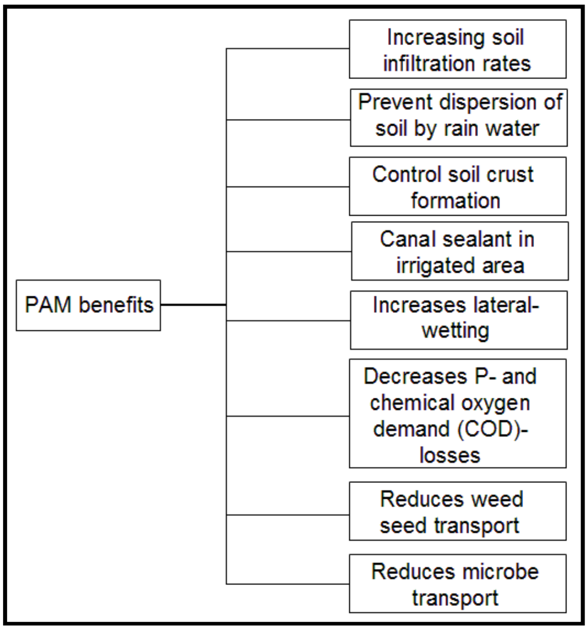

Figure 1. Main benefits provided by PAM (figure generated with information obtained from Cochrane et al. (2005), Flanagan et al. (2002), Green and Stott (2001) and Lentz (2008))

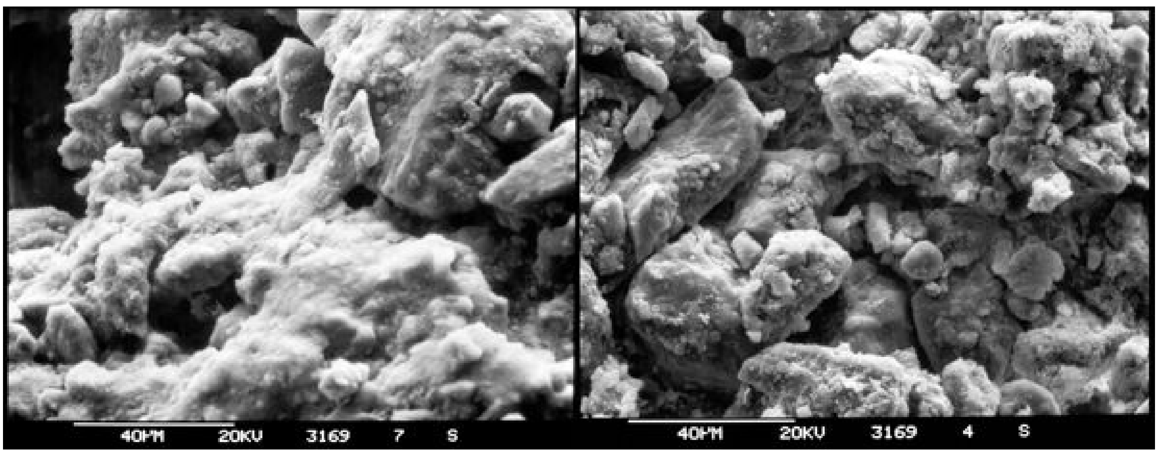

Figure 2. Comparative PAM-treated (left) and untreated (right) surface soil sub-microstructures from irrigation furrows (nominal magnification of 1500x). Source: Ross et al. (2003).

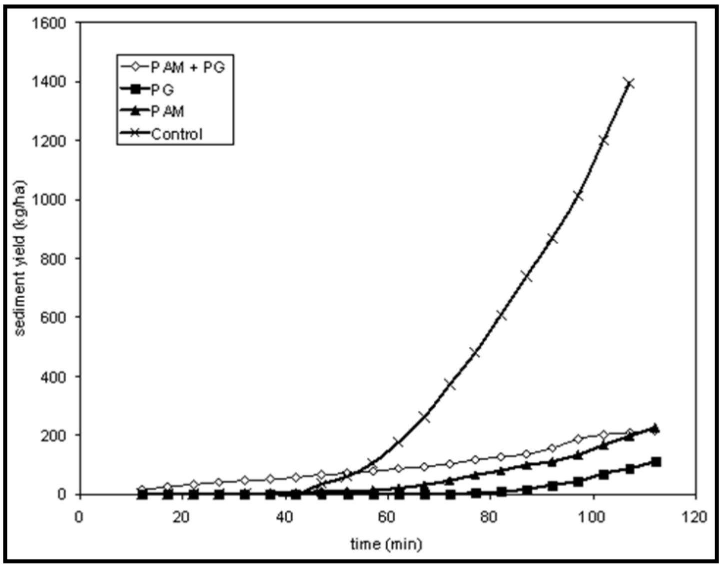

Figure 3. Cumulative soil loss vs. time from initial rainfall for control and surface amendments PG is phosphogypsum and PAM is polyacrylamide. Source: Cochrane et al. (2005)

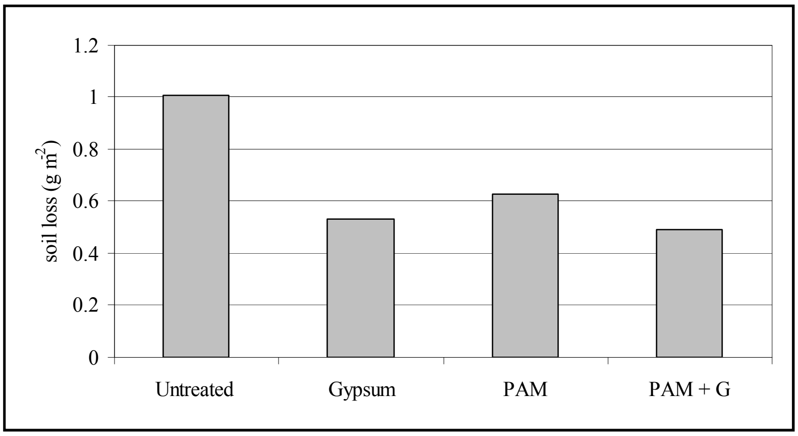

Figure 4. Soil loss in horizon A for different chemical treatments. Source: Pellegrini et al. (2002)

Figure 5. A typical situation for Brazilian Northern region (Palmas – Tocantins) where most of the roads are unpaved and suffer severe erosion in the rainy season