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Exergy Life Cycle Assessment of soil erosion remediation technologies: an Italian case study

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ABSTRACT

In this work, the primary resources assessment of four different soil erosion remediation technologies, *Geo-nets*, *Bio-mats*, *Geo-cells* and *Deep Rooting Plants* (DRP), is performed applying the approach of the Exergy Life Cycle Assessment (ELCA). The ELCA provides a comprehensive framework to assess the primary resources requirements of products by means of the conversion of primary flows of energy and raw materials absorbed by a production process into exergy.

The soil erosion technologies described in the work are analysed according to two complementary indicators: the annual average soil loss and the life cycle primary exergy requirements. The primary exergy requirement of the different applications is measured by means of three ELCA indicators: the *Cumulative Exergy Demand* (CExD), the *Thermo-Ecological Cost* (TEC) and the *Cumulative Exergy Extraction from Natural Environment* (CEENE). The specific context of the application is a highway slope of the size of 1 hectare situated along the A1 highway, near the town of Fabro (TR), in Italy.

The results indicate that DRPs are the most suitable solutions. However, TEC, CExD and CEENE indexes of these technologies suggest the existence of hidden impacts related to land use. The same result characterises also Bio-mats, the technology with the highest contribution of renewable material along the life cycle phases. In conclusion, this work shows that the use of exergy based impact indexes for the environmental impact assessment supplies a wider framework and deeper insights of the environmental performance of production processes and products.

1. Introduction

1.1. Soil erosion phenomenon

During the soil erosion process, the particles are separated from the ground surface by exogenous agents and deposited elsewhere (Blanco-Canqui et al., 2008; Kirkby and Morgan, 1980). Main agents of soil erosion are usually weather events, such as wind and rainfall, microorganisms and human activity (Kirkby and Morgan, 1980; Morgan, 1988). The intensity of the erosive action depends on several factors: the intensity of rainfalls, the length and the inclination of the ground, the presence of vegetation and the intrinsic characteristics of the soil. In Mediterranean countries, the erosion phenomenon is intensive and widespread, and it is fostered by the alternation of periods of drought and rainfall (Van der Knijff et al., 1999). According to the specific context, if no action against erosion is implemented, this phenomenon may cause eutrophication or desertification of the soil in the long term, reducing the soil available for agricultural activities and leading to severe environmental and economic consequences. Moreover, erosion may affect very large portions of bare soil: it has been estimated that about 25 million hectares of soil are affected by the erosion phenomenon in Europe (Oldeman, 1993). In Italy, the soil loss rate due to erosion is higher than 10 t/(ha y) in 30% of the territory (Morgan et al., 1998, 1989; VV.AA, 2013).

Therefore, developing and deploying appropriate solutions to prevent erosion is relevant. Their performance in contrasting soil erosion is a key factor in the evaluation of their appropriateness. However, since their widespread application may require abundant consumption of primary resources, the economic and the environmental concerns related to the life cycle of these technologies should be investigated as well. The latest market reports about the erosion remediation industry expect the global demand for

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geotextiles (the most employed soil erosion remediation technology for the protection of slopes) to reach 4323 million m^2 in 2020, increasing 8.9% annually from 2014. Road construction and erosion control account for 60% of this demand (VV.AA, 2015). Finally, national assessments indicate the protection of highway slopes as one of the major market areas for geotextiles (Shepley et al., 2002).

The *Universal Soil Loss Equation* (USLE) (1) (Wischmeier and Smith, 1978) is commonly adopted to predict the *average annual soil loss E* due to the erosion phenomenon in a slope with defined characteristics and within a given geographic context.

$$E = R \times K \times LS \times P \times C \quad [tons/(ha \cdot y)] \tag{1}$$

Where:

- *R* is the *Rainfall erosivity factor*, a climatic factor that refers to the intensity and duration of precipitations [50 ÷ 600 MJ mm/(ha h y)] (Renard and Freimund, 1994);
- *K* is the *Soil erodibility factor*, defined as the mean annual soil loss for standard conditions and geometrical properties of bare soil, without considering the application of any remediation technology [0.05 ÷ 0.7 tons h/(MJ mm)] (Wischmeier and Mannering, 1969);
- *LS* is the *Slope length and steepness factor*, a geometrical factor function of the steepness and length of the slope [1 ÷ 40] (Wischmeier and Smith, 1978);
- *P* is the *Erosion control practice factor*. Control practices include contouring and contour strip-cropping and vary with the slope steepness. *P* expresses the ratio between the soil loss where the practice is applied and the soil loss where it is not [0.5 ÷ 1] (Roose, 1977; Wischmeier and Smith, 1978);
- *C* is the *Crop management factor*. The installation of anti-erosive technologies influences the erosivity and the morphology of the soil. *C* represents the ratio between the soil loss in a slope when a given technological solution is applied and that in bare soil [0.003 ÷ 1] (Fifield and Malnor, 1990; Fifield et al., 1989; Rickson, 1995);

Theoretical details and numerical values for the application of the USLE equation can be retrieved in literature (Hashim and Wong, 1988; Lal, 1990; Roose, 1977; Singh, 1981). The effectiveness of all the available soil erosion remediation technologies is assessed by the USLE equation, evaluating their influence on the average annual soil loss of a given slope.

1.2. Objective of the work

The most suitable technology for a given context is the one that guarantees the minimum value of average annual soil loss, evaluated through the USLE Equation (1). In case more than one technology results as appropriate, the selection is generally based on purely economic criteria: however, these criteria do not properly express the environmental concerns related to the Life Cycle of the technologies, such as consumption of primary resources or pollutant or greenhouse gas emissions (Pimentel et al., 1993).

Based on these considerations, the evaluation of the primary resources requirements of different soil erosion remediation technologies is here proposed, with the aim of driving to more sustainable decisions.

Specifically, the requirement of primary resources for the production and installation of four different feasible technologies is evaluated considering their application on a highway slope in Italy. In order to assess the actual requirements, the materials inventory is computed referring to the regulation in force in Italy and the industrial practice. The methodological framework proposed to evaluate the different technologies is the *Exergy Life Cycle Assessment* (ELCA).

1.3. Soil erosion remediation technologies: common practices in the Italian context

In the European Union, the practices for preventing soil erosion are regulated by the *Eurocode 7* (Comité Européen, 1997; Frank, 2004). In Italy, the European guidelines have been adopted through the law 109/94 ("Legge 11 febbraio, 1994, n. 109," n.d.) and the related implanting regulation DPR 554/1999: technical handbooks for practical engineering applications are based on such regulations (Venti and Bazzurro, 2003).

The most commonly adopted technologies for soil erosion remediation in Italy are *Geo-nets*, *Bio-mats* and *Geo-cells*. Beside these traditional technologies, the novel practice of *Deep Rooting Plants* (DRPs) emerged in recent years (Cecconi et al., 2012; Era and Verrascina, 2013). Detailed description of such technologies can be retrieved in literature (Ayuba et al., 2014; New Jersey Department of Agriculture 2013; Pimentel et al., 1993; Rhode Island State Conservation Commettee, 2014; Toy et al., 2002). With reference to Fig. 1, a general description of these technologies is here provided.

Solution 1: Geo-nets. Geo-nets are structures made of tangled synthetic filaments characterized by high void fraction to allow for containment of topsoil. The main purpose of geo-nets is to prevent the runoff of soil due to rainfall, but they do not improve the geological and mechanical characteristics of the underlying soil. There are various procedures for the installation of geo-nets. Generally, after levelling the ground, rolls of geo-nets are laid over, slightly overlapping with each other, and secured by means of steel stakes. The nets are then filled with fertile topsoil, which is subsequently hydro-seeded. If more fertile soil is required for growing the plants, a layer is placed between the levelled ground and the geo-nets.

Solution 2: Bio-mats. Bio-mats are few millimetres thick layers of vegetable fibres, woven onto natural or synthetic nets. They are characterized by high capacity of water retention and protection against wind and their decomposition supplies nutrients to the soil. Their presence creates a microclimate within the underlying soil that favours the rooting and the growth of plants. According to the characteristics of the ground, different vegetable fibres are used: bio-mats of straw or jute are used in arid environments due to their higher capacity of moisture retention, coconut fibres are more suitable for wet areas. Bio-mats are generally employed on levelled surfaces with limited inclination and a pre-existing mantle of vegetation, and they are secured to the ground similarly to geo-nets.

Solution 3: Geo-cells. Geo-cells are three-dimension synthetic structures made of hexagonal cells arranged in a honeycomb structure. They consist in welded strips of high-density polyethylene, 1–2 mm thick and 70 mm–100 mm high. Similarly to geo-nets, geo-cells do not modify the geological and mechanical characteristics of the soil they are secured to. However, they prevent the topsoil from sliding, thus allowing the birth and growth of plants. Geo-cells are typically used on soil no more than 40° inclined. They are secured to the ground with steel stakes like geo-nets.

Solution 4: Deep Rooting Plants (DRP). Traditional methods involve the use of natural or synthetic manufactured products with the objective to support and to establish a vigorous vegetative cover to prevent soil loss caused by atmospheric agents. Usually, a mixture of Italian Rye-grass (*Lolium multiflorum Lam.*) seeds is used as vegetative cover for all the traditional erosion remediation technologies (Morgan, 2009). While traditional methods aim at