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Plants as Alternative Covers at Contaminated Sites

M. Grifoni, G. Petruzzelli, M. Barbafieri, I. Rosellini, B. Pezzarossa, F. Pedron

Abstract**—**Evapotranspiration (ET) covers are an alternative cover system that utilizes water balance approach to maximize the ET process to reduce the contaminants leaching through the soil profile. Microcosm tests allow to identify in a short time the most suitable plant species to be used as alternative covers, their survival capacity, and simultaneously the transpiration and evaporation rate of the cover in a specific contaminated soil. This work shows the soil characterization and ET results of microcosm tests carried out on two contaminated soils by using *Triticum durum* and *Helianthus annuus* species. The data indicated that transpiration was higher than evaporation, supporting the use of plants as alternative cover at this contaminated site.

Keywords**—**Contaminated sites, ET cover, evapotranspiration, microcosm experiments.

I. Introduction

PHYTOREMEDIATION refers to all technologies that exploit the natural biological processes of plants and microorganisms for treatment of contaminated soil, sediment, and water [1]. It can be used for the treatment of organic and inorganic contaminants, especially in sites with widespread contamination covering extended areas [2]. This technology is considered as a new highly promising green remediation strategy, since it shows some advantages compared to the most traditional physicochemical technologies used to recover a contaminated site. Negligible environmental impacts, low costs, easy start-up, less waste production, preservation of soil quality, and high public acceptance and more aesthetical pleasing [3], [4] are the main advantages of phytoremediation.

Based on the physical, chemical and biological interactions between plants and contaminated environmental media, different processes can be realized: phytoextraction, phytovolatilization, phytodegradation, phytostabilization, rhizofiltration, phytosorption, and phytocapping [5]–[7].

The phytoremediation techniques can be used as individual methods for the remediation of contaminated sites, as additional phases of other treatments, or as cover of a site that needs to be reclaimed and/or revegetated. This last case is named "phytocapping", "vegetative cover", "alternative covers", or "ET cover", and is part of the phytomanagement, which offers the advantage to integrate environmental and societal benefits with economic profit [8], [9].

II. Alternative Cover System

The EPA's Phytoremediation of Organics Action Team defines the "vegetative cover" as "a long-term, self-sustaining cover of plants growing in and/or over materials that pose environmental risk; a vegetative cap reduces that risk to an acceptable level and requires minimal maintenance" [10]. In particular, the ET covers are a type of vegetative cap placed over contaminated soil, landfill, or mining tailings, to prevent rainfall water from reaching polluted media [11]. The use of ET covers is an innovative kind of phytoremediation, which enhances and integrates the already well-known "landfill covers" by preventing the water percolation and contaminant spread. The novelty of this technique is the use of a water balance approach based on the main mechanisms of hydraulic control such as rainfall retention, soil moisture storage, infiltration, and ET. The soil-plant layer of an ET cover slows down the rainwater infiltration and promotes the water storage until its release through ET process [11]–[13], minimizing the water percolation and the leachate production, and consequently the risk of contamination spreading. Thus, the applicability of this technology is related to the soil's ability to store water, to the capacity of plants to intercept rainwater and to the ET power of the cover. Higher storage capacity and evapotranspirative properties of ET cover system allow to obtain a lower percolation [14].

Appropriate designs for ET cover systems need to incorporate site-specific information mainly based on soil, vegetation and climate factors.

A. Soil

The effectiveness in storing water depends on the physical and hydraulic properties of the soil such as porosity, soil texture, thickness, and organic matter content.

Finer grained soils are preferred to coarse grained soils, because of their higher fertility and water storage capacity. In the landfill, ET covers can be either monolithic ET covers or capillary barrier ET covers. The first is constructed by placing a layer, varying from 2 cm to 3 m thick, of silty or clayey silt soils on the top layer. In the second case, a strategic layer of coarse soil (sand or gravel) with a maximum thickness of 50 cm is placed at depth in the profile, to reduce water percolation and enhance the water storage through a process known as "capillary action" [13], [14]. However, the thickness of the cover depends on the required storage capacity, which is determined by climate condition of the area [11].

Soil fertility affects the ability of the soil to support vegetation and in case of low nutrient in soil, supplemental nutrients may be added to promote vegetation growth.

B. Vegetation

The ET defines the water amount that passes from soil to air due to the combined effect of direct evaporation from the soil, and transpiration through plants. Since the last one is the essential process, the most suitable plant species must be

M. Grifoni, G. Petruzzelli, F. Pedron, M. Barbafieri, I. Rosellini, B. Pezzarossa are with the Institute of Ecosystem Study – National Research Council, 56124 Pisa, Italy (phone: +39-050-3152489; fax: +39-050-3152473; e-mail: martina.grifoni @ise.cnr.it).

selected in relation to the soil conditions and to the climatic characteristics of the area in order to optimize the transpiration process.

The transpiration process in plant, bringing the water retained by the surface layers of the soil to the atmosphere, prevents the water movement along the soil profile and reduces the infiltration and runoff phenomena due to the rainwater interception by a vegetative leave cover. In addition, the vegetation for ET covers is used to minimize erosion by stabilizing the surface of the cover, and the wind-diffusion of contaminants by reducing soil particulate diffusion [12], [15]. Thus, it can be considered also as a particular kind of phytostabilization. The main characteristics to consider in the selection of the species are transpiration rate, plant size, biomass, aerial surface area, root system, duration, and harvestability [9], [16].

Since a deep root system is able to maximize the absorption of water and to reduce the erosion processes [1], grass, shrubs, or small trees that form extensive root systems are usually planted in ET covers [11]. To establish a vegetation for ET covers, seeds mixture or native plant species can be used, depending on soil and climate conditions. Generally, the autochthonous species are preferred because they are more tolerant and do not disturb the natural ecosystem [10].

C. Climate

Several climatic factors affect the ET, such as precipitation, temperature, light, relative humidity, wind, and available water in the soil. The amount, form, and timing of precipitation mainly determine the total amount of water storage capacity, that is particularly important when local vegetation is dormant, resulting in little or no transpiration [14]. Generally, the best performance of ET covers isobtained in arid or semi-arid climates because the high ET rates and the low precipitation allow to remove the infiltrated water [13], [17].

III. ET Covers Systems at Contaminated Site

The main goal of ET covers, like other conventional capping, is to prevent the spread of contaminants in the environment and not to destroy or remove them. Nevertheless, the use of vegetative cap combined with phytoremediation of contaminants (phytoextraction, phytodegradation, phytostabilization), can be suitable to increase the reclamation of the contaminated site. Moreover, the use of vegetative cover can produce additional advantages such as the improvement of the physicochemical and biological properties of the degraded soil and its possible reuse, the biodegradation of contaminants and the improvement of the aesthetic quality of the surrounding area [18], [19].

In the reclamation of contaminated sites, it is essential to reach concentrations of contaminants which are determined on the basis of the risk assessment procedures. This implies that, in many cases, a certain amount of contaminants remains in the soil even after remediation. Very often it is necessary to minimize the possibility of rainwater infiltration, in order to avoid potential leaching of residual contaminants.

As an alternative to covering with waterproof materials, it is possible to use the plant's action to increase the reclamation of the contaminated site by promoting its insertion into the environment. Even if the use of transpiration capacity of plants is already widely used to cover landfills, in a contaminated site its use is innovative. However, a more accurate feasibility study is required, because the soil can be still degraded and may contain a certain amount of contaminants, differently to clean soil that is used to cover the landfills. At lab scale, through microcosm tests, important indications on the potential of the transpiration processes can be obtained by comparing the water use and the effects of vegetation to an untreated soil.

During the assessment of the plants on the contaminated soil, some additional factors such as the specific contaminant tolerance and accumulation capability should be taken into account [9]. Generally, mixed communities of native plants (herbaceous and woody species) are selected. Species such as hybrid poplars, willows, bulrush, marsh grasses can be used for phytoremediation because they take up and "process" large volumes of soil water. The large green plants can move large amounts of soil solution through the roots. During the transpiration process, nutrients and contaminants present in the soil water are also taken up and sequestered, metabolized, or vaporized [16]. Since the whole process involves a combination of hydraulic control and phytoremediation, the purpose of the ET cover in contaminated sites is not only to maximize the ET and to prevent the infiltrations, but also to biodegrade contaminants. Therefore, ET covers design includes also the evaluation of the characteristics of the contaminated site and the choice of the best phytoremediation strategy to combined for the highest efficiency.

IV. Case Study

The preliminary steps of the ET cover feasibility test include the soil characterization and the choice of the most appropriate plant species for the specific contaminated soil. The microcosm test, a controlled semi-closed system at lab scale, was carried out to evaluate in a short time the soil evaporation, the survival and growth ability of the two different plant species and their transpiration rate.

A. Experimental Procedure

The soil used in this work was collected from a contaminated industrial site located in northern Italy. The site was subdivided by two Thyssen polygons, A and B, from which soils named A and B were collected.

Soil samples were air dried and ground to pass through a 2-mm sieve in order to separate the soil fine fraction to be analyzed. Soil properties were determined according to standard methods [20]. Soil pH and electrical conductivity (EC) were determined using a glass electrode in a soil/water ratio of 1:2.5 and 1:2, respectively. Cation-exchange capacity (CEC) was measured using barium chloride (pH 8.1), soil texture was assessed using the pipette method. Organic matter (OM) content was measured with RC-412 Multiphase Carbon Determinator and N content with FP-528 Nitrogen/Protein

Analyzer for Organic Samples.

On the basis of preliminary experiments (data not reported), two plant species were selected to be grown on the contaminated soil: *Triticum durum* var. Grazia and *Helianthus annuus* var. Marina.

The seed germination tests were carried out in Petri capsule, and after 7 days the germination rates were about 94% either for *T. durum* and for *H. annuus*. Microcosm experiments were conducted in 250 mL pots by sowing the two plant species in 200 g of soil and using approximately 50 and 15 seeds for *T. durum* and *H. annuus*, respectively. The soil used in the microcosm experiments was prepared by eliminating the coarser material, but without sieving to 2 mm, in order to obtain samples representative of the real situation. Two groups of microcosms per soil samples were set up, for a total of 20 microcosms: a group sown with *T. durum* and a group sown with *H. annuus*, each composed of three replicates, and a group of non-vegetated microcosms composed of four replicates.

The initial steps of the microcosm experiments were carried out in a growth chamber in controlled conditions: 14 h of light, with a temperature of 24 °C, and 10 h in dark conditions at 19 °C. Relative humidity was maintained at 65%. 10 days after sowing the plants have been moved to the outside of growth chamber to avoid affecting the ET process.

ET was measured by the gravimetric method [21], [22]. After ten days from sowing, the microcosms were weighted every two days recording the weight loss and replacing the amount of water lost by transpiration, up to reach the starting dose of 25 g of water, established based on need of the plants. In order to homogeneously wet the soil, a glass straw was placed inside each pot. All microcosms were kept in the same conditions of light exposure, temperature, and relative humidity during all their growth period. A total of 22 additions for each pot were carried out, until the first signs of plant suffering appeared. Microcosm trials lasted about 35 days.

The ET was assessed comparing the mean weight loss of the three different groups of microcosms in the last 22 days of growth.

B. Results and Analysis

Since ET covers technique is based on the capacity of soil to store rainwater and to eliminate it through ET processes, some physical soil parameters were evaluated. In addition, the assessment of the fertility parameters indicated if the soil conditions were suitable for plant growth. The results (Table I) suggested that the main physical characteristics of the soil were sufficient for the short growing period of microcosm experiments and no fertilization practice was necessary.

The data from ET test (Fig. 1) show that *H. annuus* had a generally higher capacity of ET than *T. durum*, in both soil samples.

After two days from the first water addition (about twelve days from sowing), about 14 g and 20 g of water evaporated from *T. durum* for *H. annuus* respectively, either in A and B soil samples.

TABLE I
SOIL PROPERTIES

Parameter	Soil A	Soil B
pH	8.72	9.11
EC (µS/cm)	608	545
CEC ($cmol_{(+)}$/kg)	18.9	15.4
Sand (%)	57.2	68.4
Silt (%)	23.3	19.7
Clay (%)	19.5	11.9
OM (%)	1.59	0.92
N	0.15	0.09

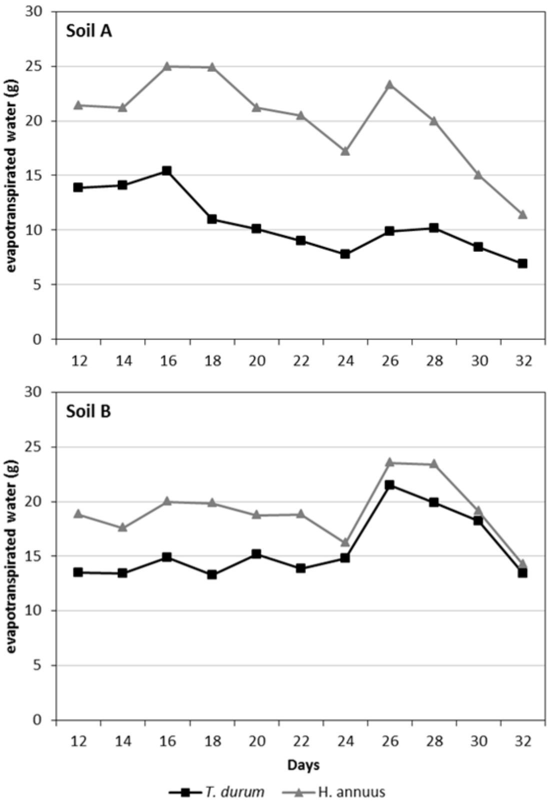

Fig. 1 Amount of eliminated water in the ET process in soil A and B. Data are the mean of three replicates

A decreasing trend of ET process with time was observed for both microcosms. In soil A, the highest amount of eliminated water, 15 g and 25 g for *T. durum* and *H. annuus,* respectively, was detected during the third determination, then it decreased. In soil B, the decreasing trend was noted only after the seventh determination, with peaks of 21.5 g and 23.5 g of lost water for *T. durum* and *H. annuus*, respectively. The initial determinations of evapotranspired water were quite similar, with an average value of about 18.5 g for *H. annuus* and around 13 g for *T. durum*. In the microcosms vegetated with *H. annuus*, the amount of eliminated water during ET process was on average 2 (soil A) and 1 (soil B) times higher than that eliminated in microcosms grown with *T. durum.* Consequently, the *H. annuus* was the species with the highest rate of ET: 100% was recorded after 16 days from sowing in microcosms set up with soil A, and 94% after about 27 days in microcosms prepared with soil B. The minimum quantity of water lost was found in all microcosms after 32 days from sowing, i.e. at the end of the experiment, except for *T. durum* in microcosms with soil B, where the minimum value was observed at the fourth determination, approximately 18 days from the starting of the test.

In general, in non-vegetated microcosms the evaporation rate was always lower than in the vegetated microcosms. The average amount of water lost by evaporation (Fig. 2) was rather constant, with values ranging from 6 to 8 g, in both soils.

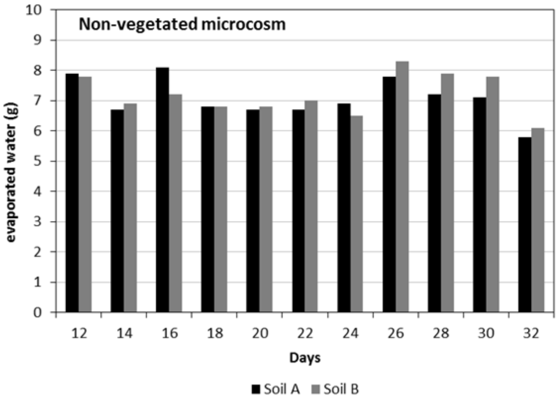

Fig. 2 Amount of eliminated water in the evaporation process in non-vegetated microcosms. Data are the mean of four replicates

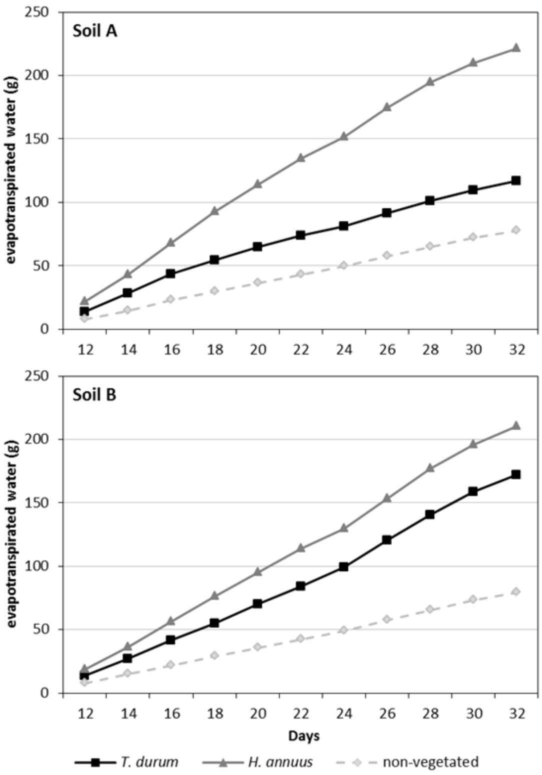

Fig. 3 Cumulative amount of water lost in the evaporation and transpiration processes in soil A and B. Data are the mean of three replicates

A similar pattern (Fig. 3) of total amount of water eliminated by ET process during the experiment was observed in both soils. The highest cumulative amount of evapotranspirated water, about 220 g, was detected in microcosms set up with soil A planted with *H. annuus*, whereas the corresponding value obtained with *T. durum* was about 2 times lower.

The data from non-vegetated microcosms allowed either to estimate the amount of water that is lost during the evaporation process or to quantify the transpiration process in vegetated microcosms. Fig. 4 highlights the low transpiration of *T. durum* species, especially in soil A where the most important contribution to ET was the evaporation. However, the data from *H. annuus* indicate that more of 65% of added water has been transpired by plants, while about 20% is evaporated from the soil.

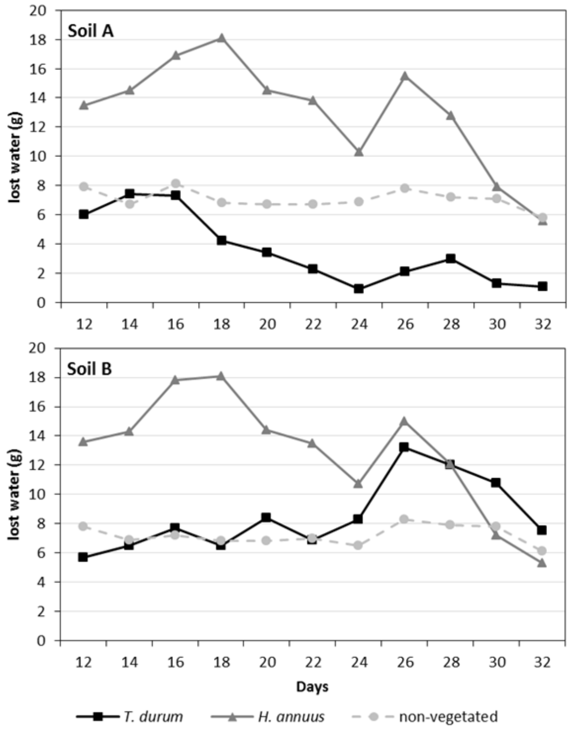

Fig. 4 Average amount of water eliminated in the evaporation and transpiration processes in soil A and B

V. Discussions and Conclusion

Results showed that, in the contaminated site under study, phytoremediation with plants growing in the "engineered" way of alternative covers, could be successful. Plants are able to disperse the water before it reaches deeper layers through absorption and ET processes, and the movement of polluting elements to the aquifers is drastically reduced. At the same time, the phytoremediation actions, such as phytoextraction and phytodegradation, may act towards these pollutants at the same time. It must be underlined the importance of the soil textural properties which should allow water infiltration with a minimum drainage during periods of vegetative dormancy, thus providing an adequate reservoir of water in the soil that can be exploited by plants. Finally, the growth of plants enhances the microbial community, which in turn may promote degradation of organic contaminants.

The use of ET cover is of great interest either in the recovery of degraded areas, where the soil has lost many of its filtering and deep water protection properties, and when it is necessary to regulate the flow of water that infiltrates the soil. The presence of a vegetative cover can ensure an effective hydraulic control since the rainwater interception by plants prevents or reduces the infiltration processes. In the meantime, the root system absorbs considerable amounts of infiltrated water in the top layer of soil and then disperses it by transpiration.

The results of the ET feasibility test revealed a higher effect of the transpiration process of the two plant species compared to the soil evaporation process. The plants were able to remove over 90% of the added water. Among the two plant species, *H. annuus* showed the highest levels of transpiration, while the two contaminated soil had the same evaporation rate.

In conclusion, the data obtained here suggest the use of combined phytoremediation technologies as a valid solution to the specific problems of the examined contaminated soils.

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