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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Invasion impact of the nitrogen-fixing shrub *Genista aetnensis* on Vesuvius Grand Cone

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Abstract

Vesuvius Grand Cone dominates the landscape of Napoli Gulf with its distinguishable grey bare slopes, exposed to continuous surface erosion processes and rock falls which have been hindering the development of the vegetation after the last volcanic eruptions (occurred in 1944). In the last 60 years the development of the vegetation became evident along some portions of the Grand Cone. This process is facilitated by the upslope expansion of the *Genista aetnensis* (Biv.) DC., a plant endemic of the Mt. Etna (Sicily) and of Eastern Sardinia, which has been imported to Mt. Vesuvio in 1906 as part of a reforestation program of the Vesuvius slopes. Vesuvio National Park, within the MED project For Climadapt, is conducting a multidisciplinary research program aiming at evaluating the effect of the *G. aetnensis* invasion of the Vesuvius Grand Cone, both at landscape and ecosystem level, also in light of current and predicted climatic changes. An intensive field investigation has been designed to explore the eco-hydrological conditions facilitating the expansion of the *G. aetnensis*. Plant species and soils have been collected both underneath and outside the cover of *G. aetnensis* canopies to gather relevant information about the interaction of the *G. aetnensis* with the other species as well as to explore the small scale spatial gradients of soil fertility induced by the *G. aetnensis*. Two permanent stations have been installed to monitor the differences in soil water content, soil temperature and air temperature between inside and outside the canopy cover. The collected data evidence that *G. aetnensis* tends to create an island of fertility by increasing the organic matter content in the soil and improving the soil water retention properties. Moreover, the *G. aetnensis* mitigates the daily soil temperature excursions, reducing the exposure of seeds to extremely high temperature values, particularly during the growing season, and the direct soil evaporation loss. These results suggest that the invasion of *G. aetnensis* can promote alternative successional trajectories that may dramatically affects vegetation dynamics. Further studies are needed to identity specific management practices that can limit the spread and impact of this species.

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1. Introduction

Mt. Vesuvius dominates the central part of the Campania Region coastline and it represents the most characteristic morphological feature of the landscape of the Gulf of Naples, with its distinctive reddish-gray crater summit, named as Grand Cone, formed during the eruption of AD 79 (Fig. 1).

The slopes of the Mt. Vesuvius at the bottom of the Grand Cone have been historically interested by reforestation programs, particularly after the latest eruptions of the early 20th century, aiming at reducing the exposure of the bare slopes to water erosion and shallow landslides. Reforestation programs never interested the Grand Cone itself, as this is characterized by very steep slopes (in average 40-45°) covered by unconsolidated lapilli and gravels, exposed to frequent water erosion and gravitational sliding. In addition, these pyroclastic deposits are organic matter and nitrogen poor, with an extremely low water holding capacity that hinders the colonization by vascular plants.

Genista aetnensis (Biv.) DC., a plant endemic of Mt. Etna and Eastern Sardinia, was firstly introduced during the reforestation programs of Mount Vesuvius after the eruption of 1906 and, more extensively, in the 1945-1955 decade following the last eruption that occurred in 1944 [1]. This plant, being a nitrogen fixing species, was selected because it colonizes andosols with an ability much more pronounced than the naturally occurring indigenous brooms (*Cytisus scoparius* and *Spartium junceum*).

In the last decade *Genista aetnensis* (thereafter *Genista*), thanks to its pronounced pioneering attitude, has been expanding over the Grand Cone, facilitating the colonization of other species especially herbaceous. However, a so rapid biological invasion by a non-native species is a serious threat to ecosystem functioning [2]. In spite of the dramatic landscape impact of *Genista* (Fig. 1), no studies addressed the ecosystem effects of this invasive plant. In this context, the National Park of Vesuvius in collaboration with the University of Naples Federico II is now conducting a multidisciplinary research program within the MED project "For Climadapt", aiming at evaluating the impact of *Genista* invasion over the Grand Cone slopes. The preliminary results of this research program are presented in this paper, focusing on the effects of *Genista* on soil pedogenesis, hydrological processes and natural vegetation.

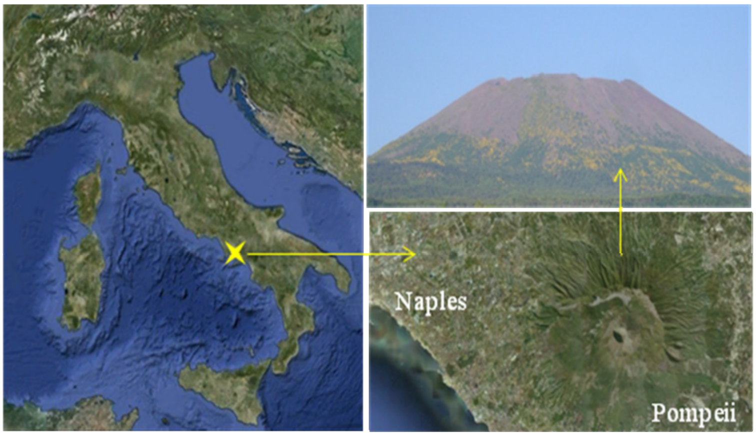

Fig. 1. Location of the Mt. Vesuvius with respect to the Italian Peninsula (left) and the cities of Naples and Pompeii (lower right). Upper right: picture of the Mt. Vesuvius taken in late spring with a view of the Grand Cone (note the yellow flowers of *Genista aetnensis* at the toe).

2. Materials and methods

2.1. Plant species and study sites

Genista (Fabaceae) is a multi-stemmed nitrogen fixing shrub. At the study sites, this broom has loose canopies that attain a diameter up to 3 m, with crown reaching a height up to 5 m. The experimental site is located on the east-facing side of the Vesuvius Grand Cone, along a slope with a steepness of 40º to 45º, at an elevation about 1,000 m a.s.l. The substrate is constituted by coarse and deep soils with a high content of lapilli and scoriae ejected in recent eruptions (1944). The plant community is a primary succession over a bare and physically unstable substrate. The Grand Cone has been firstly colonized by the endemic fruticose lichen *Stereocaulon vesuvianum* and the small perennial herb *Rumex scutatus* subsp. *scutatus*. As mentioned in the introduction, Agostini [1] reported that *Genista* has been imported to Mt. Vesuvio after 1906. Nowadays, after 106 years from the first plantation, *Genista* became the dominant plant species on the Vesuvius Grand Cone.

The area has a Mediterranean climate with a cold winter and a relative hot, dry summer. Mean monthly temperature ranges between 21.6 °C (July) and 5.7 °C (January). Mean annual rainfall is high (about 1100 mm), distributed in winter (408 mm), spring (171 mm), summer (116 mm) and autumn (399 mm). These average climatic values have been estimated from 20 years of registrations of the meteorological station located at the Vesuvius Observatory located at an elevation of 612 m a.s.l., about 2 km far from the study site.

2.2. Field measurements

Field measurements were carried out to: (1) assess the effects of *Genista* on soil physical and chemical characteristics; (2) on the above- and below-ground microclimate and soil water content regime; (3) evaluate the effects of *Genista* on the distribution of coexisting species.

2.3. Genista fertility island

The field surveys have been performed in two typologically different locations in order to asses the influence of the *Genista* shrubs on the local factors affecting the propagation of the vegetation: the canopy crown area directly influenced by litter and roots (hereafter referred to as IN), and the area located far from the shrubs (hereafter referred to as OUT) located at least 3 m far from the canopy edge of the nearest shrub (Fig. 2).

Soil was sampled inside (IN) and outside (OUT) 20 randomly selected *Genista* plants. *Genista* plants were selected in small clusters of at least 20 individuals with an average age of 35 years and height of 3-4 m. At each sampling location three replicates were collected and subsequently pooled. Soil samples (~2 kg each) were collected from the topsoil after removal of litter layer (0-20 cm) in the Spring 2010 (May-June), considered the best time for soil collection [3]. Samples were packed in polyethylene bags, transferred to laboratory within 3 hours and sieved at 2 mm mesh, with subsequent quantification of the resulting fractions (>2 mm and <2 mm).

Nine parameters were measured to assess the soil quality of the thin soil fraction (<2 mm). Physical and chemical properties of soils were determined by standard methods [4]. Particle size distribution analysis was carried out by the pipette method; pH and electrical conductivity were measured in 1:2.5 soil:water suspensions and 1:5 soil:water extracts, respectively; organic C content was assayed by chromic acid titration method; total N was determined by flash combustion with a CNS Elemental Analyser (Thermo FlashEA 1112), and cation exchange capacity was measured after soil treatment with a barium chloride and triethanolamine solution at pH 8.2. Soil water repellency has been assessed by the drop infiltration method of air dried soil samples as reported by [5].

Fig. 2. A picture of a *Genista aetnensis* with depicted the two sampling zones: black dashed line separate the area under the shrub canopy (IN) and the open area (OUT).

2.3.1. Litterfall and standing litter of Genista

The amount of standing litter was measured in 20 x 20 cm square frames randomly located in the two sampling areas (IN and OUT) in 20 randomly sampled Genista plants. Organic debris were dried (+60°C) and weighted after constant weight was reached. To assess the input C and N from *Genista* litter, litterfall in the field was quantified. Litter production was measured in the IN and OUT areas by placing plastic traps (28 cm x 18 cm x 14 cm for each side and height, respectively) standing 10 cm above the ground. The trap bottoms were wrapped with 1-mm-mesh plastic screen. Globally, we placed 20 traps (10 for each area) under randomly selected *Genista*. Litterfall was monthly collected between August 2011 and December 2012. Collected samples were placed in plastic bags and transported to the laboratory, sorted into species, and dry weighted (60°C until constant weight was reached).

2.3.2. Genista effects on above- and below-ground microclimate

Abiotic environmental conditions under *Genista* (IN) and outside the canopy (OUT) were characterized by measuring above- and below-ground microclimate as well soil water content. Two monitoring stations have been installed in the IN and OUT areas of *Genista,* respectively. Each station was equipped with 5TM Decagon sensors, consisting of capacitance sensors measuring the soil water content, integrated with thermistors for monitoring the soil temperature. These sensors have been horizontally inserted into the soil at 5 cm and 20 cm depths, providing an estimate of the soil content in a volume of 0.3 liters. Soil temperature is also employed for correcting soil water content data, since 5TM sensors exhibit some sensitivity to the temperature. According to the sensor specifications, the accuracy of the measured soil water content is about ± $0.03 m^3/m^3$, after using Topp equation [6] for transforming the soil apparent dielectric permittivity in soil water content. Each station was also equipped with an air temperature and relative humidity sensor, positioned 5 cm above the ground surface.

All data have been collected for a period of one year, from January 2012 to January 2013, with a time resolution of ten minutes. In addition, during summer 2012, soil surface temperature outside and under *Genista* canopy was recorded by IR analysis using a thermographic camera (Fluke Yi25).

Photosynthetic active radiation (PAR, wavelength between 400 and 700 nm) was measured with a LICOR LI-250A at a height of 0, 50, 100, and 200 cm above the ground, outside and under the canopy of 5 randomly selected *Genista*. Measures were done in the IN and OUT areas under bright, sunny conditions around mid-day in July 2012.

2.3.3. Genista effects on plant community structure

Vegetation surveys were carried out to assess the association of *Genista* shrubs with coexisting plant species. Twenty randomly selected *Genista* (IN) and corresponding OUT area were analyzed. For each shrub, living biomass and species richness of plant community were assessed in 2011 at the end of the growing season (August). Vegetation survey were done by randomly placing squared sampling frames (20 x 20 cm) inside and outside *Genista* shrubs. The above-ground living plant biomass within the sampling frames was cut with scissors and harvested. Living biomass and litter mass were expressed as dry weight after oven drying at 60 °C after dry constant weight was reached. Significant differences of plant cover, species richness, and plant biomass between inside and outside *Genista* shrubs, were tested with ANOVA statistics using the software package STATISTICA 7 (Stat-Soft Inc., US).

3. Results

3.1. Genista fertility island, litterfall and effects on plant community structure

IN and OUT soils have a sandy texture not significantly affected by the presence of *Genista* canopy (data not shown). IN soil has higher total N, organic C, extractable phosphorus, electrical conductivity, and CEC compared to OUT soil (Fig. 3). Soil pH was slightly, but significantly reduced in the IN soil compared to OUT (Fig. 3). Soil in the OUT area was not water repellent, with a water drop penetration time < 1 s. In contrast, soil collected under *Genista* shrub was highly hydrophobic, with vey high water penetration time (> 4 hours). *Genista* litterfall was negligible outside the canopy (OUT area) but was high in the IN area with more than 1,000 g m^{-2} $year^{-1}$ of litterfall (Tab. 1). Litterfall of other species was, in both sampling areas, much lower compared to *Genista* litterfall (Tab. 1). *Genista* standing litter was significantly higher in the IN area compared to the open zone (OUT) (Tab. 1). Plant biomass and species diversity were higher under *Genista* canopy (IN) as compared to outside (OUT) (Fig. 4).

Tab. 1. Litterfall and standing litter under *Genista aetnensis* shrubs (IN) and from the open area (OUT). Data are mean ±1SE for all parameters, different letters indicate statistically significant between zone differences (t-test; $P < 0.05$).

Parameter	Sampling area	
	OUT	IN
Genista litterfall (g m^{-2} $year^{-1}$)	28±15 b	1144±181 a
Litterfall of other species (g m^{-2} $year^{-1}$)	23±11 b	77±25 a
Standing litter (g m^{-2})	5±3 b	1121±75 a

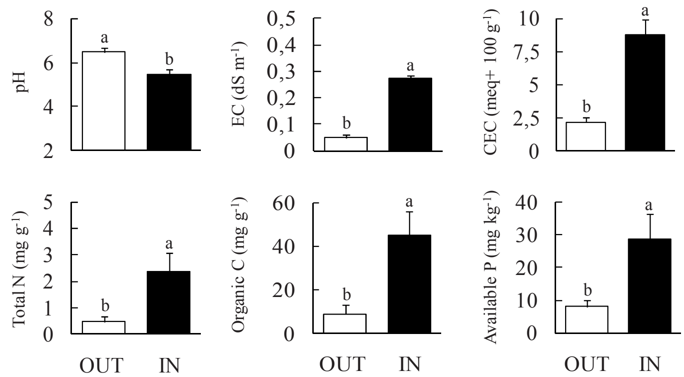

Fig. 3. Soil parameters sampled in the top 20 cm under *Genista aetnensis* shrubs (IN) and from the open area (OUT). Data are mean +1SE for all parameters, different letters indicate statistically significant between zone differences (t-test; $P < 0.05$).

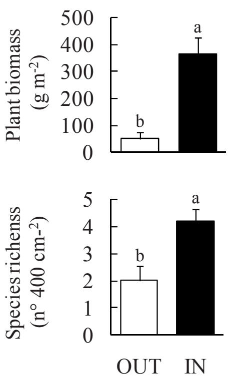

Fig. 4. Plant biomass and species richness outside (OUT) and under (IN) *Genista aetnensis* shrubs. Data are means +1SE, different letters indicate statistically significant between zone differences (t-test; $P < 0.05$).

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3.2. Genista effects on above- and below-ground microclimate

Fig. 5 shows the probability density of the soil water content measured at 5 cm depth, both under (IN) and outside the canopy (OUT). Soil moisture outside the canopy switches between two preferential states: one dry, from June to September, and the other wet, from October to May. In the wet period, the soil water content tends to be larger than 0.06 m^3/m^3 and it exhibits sharp peak values during the rainfall events as result of infiltration, redistribution and drainage processes. In the dry period, surface evaporation induces a reduction of the preferential soil content value to around 0.03 m^3/m^3. The transition from the dry to the wet states occurs rapidly, as soon as the first autumn rainstorms occur.

A gradual transition between the dry and the wet stages can be instead observed inside the canopy. This gradual transition can be attributed to two concurrent effects. First, the rainwater interception by the litter deposited under the canopy, which can retain part of the initial rainfall volume. Second, the observed water repellency of the soil under the canopy may induce a significant delay in the imbibitions process starting from the dry conditions established during the summer season. Indeed, recent studies confirmed that water repellency can enhance the hysteresis of the soil hydraulic properties, which significantly influences the infiltration dynamics [7].

Fig. 6 compares the probability density curves of the soil temperature measured at 5 cm under (IN) and outside the canopy (OUT) respectively. It is interesting to observe that *Genista* canopy reduces the occurrence of the extreme temperature values above 30 °C. A similar feature can be observed also by examining the soil temperature measured at 20 cm depth. IR analysis showed that surface soil temperature outside the canopy often exceeds 60°C. Differently, soil under *Genista* canopy was much cooler, with temperature ranging from 25°C to 35°C (Fig. 7). Significant light attenuation occurred inside the *Genista* canopy whilst no attenuation was recorded in the OUT area (Fig. 8).

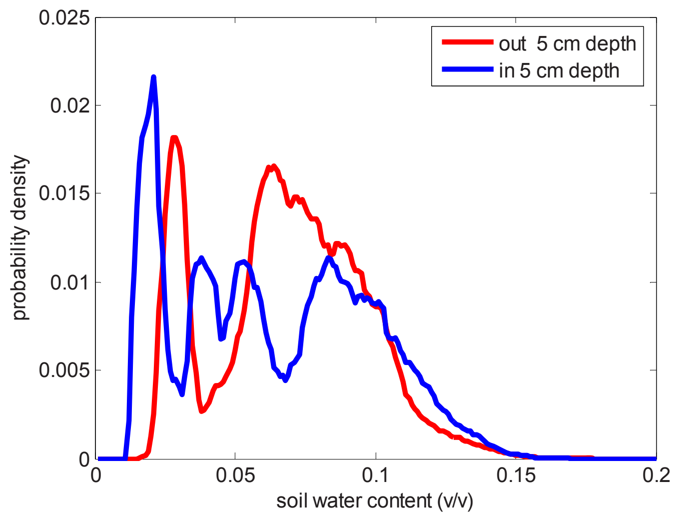

Fig. 5. Probability density of the soil water content measured at 5 cm depth outside (OUT) and under (IN) the canopy.

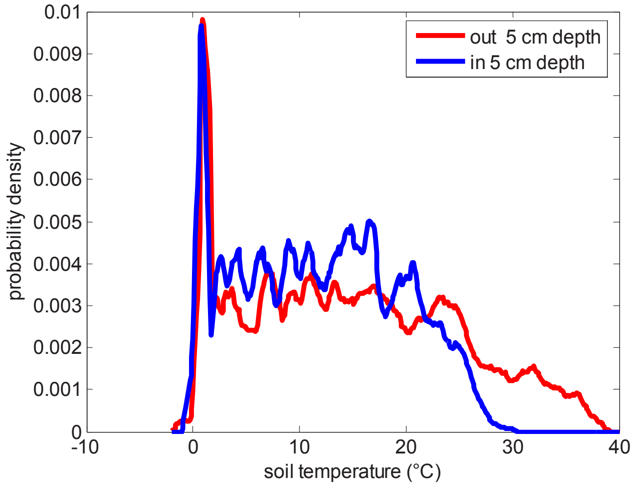

Fig. 6. Probability density of the soil temperature measured at 5 cm depth outside (OUT) and under (IN) the canopy.

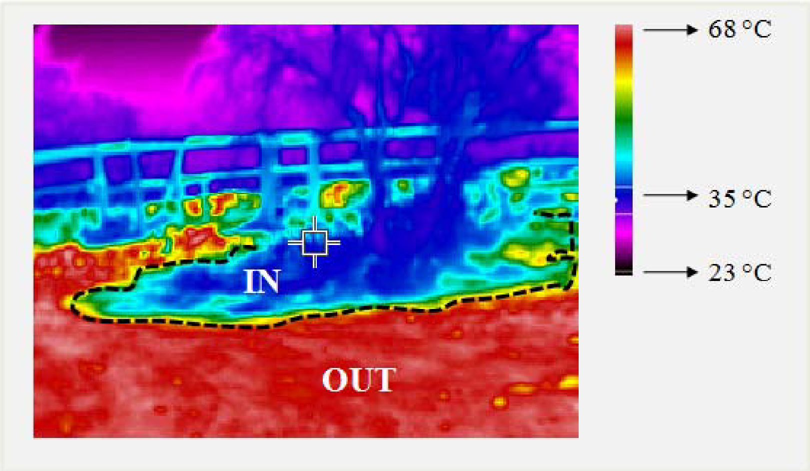

Fig. 7. IR image collected in a sunny, summer day (13 August 2012, air temperature was +28°C) showing soil surface temperature under (IN) and outside (OUT) the canopy of a *Genista aetnensis* shrub (note, in the background, a fence). Black dashed line indicate the edge of soil shaded by the shrub canopy.

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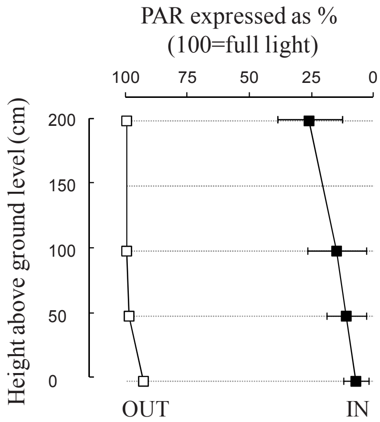

Fig. 8. PAR attenuation along the vertical profiles inside (IN) and outside (OUT) the canopy of *Genista aetnensis* shrubs. Data are mean ±1SE.

4. Discussion

The biological invasion of *Genista*, in the last 60 years, dramatically changed the landscape appearance of the Vesuvius Grand Cone. Here we reported that *Genista,* under its canopy, builds-up an island of fertility, by changing the soil physico-chemical properties and modifying the soil hydrological and microclimatic regime. Such changes in soil quality, coupled with a buffering of microclimate under its canopy, drive to an enhanced colonization by several plant species. In other word, this plant act as key stone species by building a new, less stress prone environment that allow the colonization of less stress adapted species [8].

Genista colonization on the Grand Cone slopes initiates a rapid pedogenetic process that drives to an increase of C and N stocks, available P, cation exchange capacity and a reduction of soil pH. These changes of soil quality are typical of nitrogen fixing shrubs that colonize the early stages of primary succession over barren substrates (e.g. [9]; [10]). Significant differences could be also observed in the soil water dynamics between sites located under and outside the canopy, respectively. These differences could be related to the fact that the structure-forming effect of the organic matter influences the water retention properties, particularly in such coarse-textured soils [11] and at suction heads around those generally identified with the field capacity conditions [12]. A distinctive dry-to-wet gradual transition could be also observed in the soil under the canopy in autumn, which could be attributed to the effect of the canopy and litter interception as well as to the enhanced water repellency of this soil from initially dry conditions. The soil temperature regime is also significantly influenced, reducing the upper extremes to values below thirty degrees. Monitoring the ecophysiological status of facilitated plant species are required to establish if the ameliorated pedological and microclimatic conditions under *Gensista* canopy effectively alleviate the stressful ecological conditions.

As a consequence, plant rooted under adult living *Genista* can benefit of milder temperatures and larger available water content, particularly during the growing season. Such obvious amelioration of microclimatic conditions, coupled with the improvement of soil quality and hydrological properties explain the observed positive effects on the biomass of coexisting species ([8]; [13]). In fact, at community level, the spread of *Genista* fosters plant colonization and increase local species diversity of native species. However, some exotic species (e.g. *Robinia pseudoacacia*) take advantage of the ameliorate pedological and microclimatic environmental conditions under the canopy. Potentially, this could drive to the spread of other, more resources demanding exotic species [14] promoting alternative successional trajectories that may dramatically affects biodiversity. Long-term vegetation monitoring, indeed, is required to clarify the consequences of this invasion on vegetation dynamics and ecosystem functionality. Further studies are needed to identity specific management practices that can limit the spread and impact of this species.

Acknowledgements

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