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Root morphology and biomechanical characteristics of high altitude alpine plant species and their potential application in soil stabilization

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ABSTRACT

Glacial forefields host young, poorly developed soils with highly unstable environmental conditions. Root system contribution to soil stabilization is a well-known phenomenon. Identifying the functional traits and root morphology of pioneer vegetation that establish on forefields can provide information useful in the practical application of plants in land restoration of high altitude mountain sites.

This study aims to gather information on the root morphology and biomechanical characteristics of the 10 most dominant pioneer plant species of the forefield of Lys Glacier (NW Italian Alps).

X-ray Computed Tomography (X-ray CT) was used to visualize and quantify non-destructively the root architecture of the studied species. Samples were cored directly from the forefield. Data on root traits such as total root length, rooting depth, root diameter, root length density and number of roots in relation to diameter classes as well as plant height were determined and compared between species. Roots were also tested for their tensile strength resistance.

X-ray CT technology allowed us to visualize the 3D root architecture of species intact in their natural soil system. X-ray CT technology provided a visual representation of root–soil interface and information on the exact position, orientation and elongation of the root system in the soil core. Root architecture showed high variability among the studied species. For all species the majority of roots consisted of roots smaller than 0.5 mm in diameter. There were also considerable differences found in root diameter and total root length although these were not statistically significant. However, significant differences were found in rooting depth, root length density, plant height and root tensile strength between species and life forms (dwarf shrub, forb, graminoid). In all cases, root tensile strength decreased with increasing root diameter. The highest tensile strength was recorded for graminoids such as *Luzula spicata* (L.) DC. and *Poa laxa* Haenke and the lowest for *Epilobium fleischeri* Hochst.

The differences in root properties among the studied species highlight the diverse adaptive and survival strategies plants employ to establish on and thrive in the harsh and unstable soil conditions of a glacier forefield. The data determined in this study could provide a significant contribution to a database that allow those who are working in land restoration and preservation of high altitude mountain sites to employ native species in a more efficient, effective and informed manner.

1. Introduction

Glaciers in alpine regions are affected by climate change twice as much as the global average with respect to other ecosystems (Bradley et al., 2014) which results in accelerated glacial retreat. Retreating glaciers expose young soils that are low in nutrients (carbon and nitrogen) (Bradley et al., 2014; Lazzaro et al., 2010) and highly unstable (Matthews, 1999). Mass wasting and erosion processes are common in these forefields creating an inhospitable environment for plant colonization (Siomos, 2009). Vegetation establishment on glacier forefields requires species with strong adaptive strategies and with high stress and disturbance tolerances (Robbins and Matthews, 2009). In spite of the harsh environment, vegetation cover increases quickly (Matthews, 1999) due to the rapid colonization of pioneer species. Pioneer species can grow quickly on nitrogen poor soils due to their high reproduction capacity and photosynthetic activity, (Stöcklin and Bäumler, 1996)

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and tolerance against abiotic stresses e.g., extreme temperatures, ultraviolet radiation, atmospheric pressure, shortage of mineral nutrients (Jones and Henry, 2003; Körner, 2003; Stöcklin et al., 2009).

Successful colonization and establishment of alpine species on glacial forefields may provide important information on the practical aspects of land reclamation and habitat restoration (Robbins and Matthews, 2009). Root traits (architectural, morphological, physiological and biotic) play an important role in both the physical and, even though the present study will not discuss further, also the chemical development of young soils (Bardgett et al., 2014; Massaccesi et al., 2015) bringing about increased structural stability in the forefield (Bardgett et al., 2014) and decreasing the frequency and severity of any mass wasting and erosion processes. The biomechanical characteristics of roots such as tensile strength is a useful parameter for the quantification of the reinforcement potential; in particular for quantifying the added soil cohesion provided by plant roots. Determining the tensile strength of roots and their distribution in the soil profile can provide information on the increased shear strength of the soil provided by root reinforcement which can also determine plants' resilience to solifluction, frequently occurring in a periglacial environment (Jonasson and Callaghan, 1992). Quantitative data on root traits and architecture is one of the most significant variables considered when plants are evaluated for soil stabilization (Stokes et al., 2009). However data on root traits of alpine species remains scarce (Hu et al., 2013; Jonasson and Callaghan, 1992; Nagelmüller et al., 2016; Onipchenko et al. 2014; Pohl et al., 2011; Zoller and Lenzin, 2006) which limits our understanding of the role these plants can play in root-soil interactions on the forefield.

Traditional techniques applied to examine the root system such as rhizotron or mini rhizotron, the use of paper pouches, synthetic soil media are all limited by the visual tracking of roots and/or creating an artificial environment that can lead to distorted results. Destructive root phenotyping methods can also produce misleading results (Mooney et al., 2012) as they involve the separation of roots from the soil media meaning the relationship of the roots to the soil and to each other can no longer be observed (Pierret et al., 2005). Additionally, repeated analysis on the same root system over time cannot be carried out e.g., dynamics of root growth or derivation of root demography (Koebernick et al., 2014).

Non-destructive imaging techniques such as Neutron Radiography, Magnetic Resonance Imaging (MRI) and X-ray Computed Tomography (X-ray CT) have been effectively used in root phenotyping as they overcome the limitations of traditional techniques and are able to provide results on intact root systems in undisturbed soil. Research involving modeling (e.g., Water Erosion Prediction Project (WEPP) or Chemicals, Runoff and Erosion from Agricultural Management Systems Research involving modeling (e.g., Water Erosion Prediction Project (WEPP) or Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS)) also benefits from the enhanced quality of numerical data on root traits provided by these state of the art techniques (Lobet et al., 2015; Tasser and Tappeiner, 2005). (CREAMS)) also benefit from the enhanced quality of numerical data on root traits provided by these state of the art techniques (Lobet et al., 2015; Tasser and Tappeiner, 2005).

X-ray CT has already been successfully employed in many studies focusing on plant roots (e.g. Aravena et al., 2011; Mooney et al., 2006; Pierret et al., 1999; Wantanabe et al., 1992) to obtain clear, 3D images of intact root systems in the soil without the paramagnetic (materials that are attracted by an externally applied magnetic field and form internal, induced magnetic fields in the direction of the applied magnetic field. (Boundless, 2016)) impact on the image quality found in MRI (Mooney et al., 2012; Koebernick et al., 2014). Whilst the majority of X-ray CT studies have been carried out on agricultural plant species such as wheat (Jenneson et al., 1999; Gregory et al., 2003; Mooney et al., 2006), maize (Lontoc-Roy et al., 2006), soybean (Tollner et al., 1994), potato (Han et al., 2008) and tomato (Tracy et al., 2012), a few studies can be found on tree roots (Pierret et al., 1999; Kaestner et al., 2006; Paya et al., 2015) and grasses (Pfeifer et al., 2015). As yet, no research has been carried out on the root architecture of alpine species under natural soil conditions using the X-ray CT.

In the majority of these studies, sieved, pre-prepared, low organic matter soils were used as the plant growth matrix, as the greater amount of organic particles can make root differentiation from soil particles more difficult, hampering root segmentation (i.e. the process of partitioning a digital image into multiple segments). Moreover, the moisture distribution within undisturbed soil is more inconsistent which may also complicate the image segmentation process due to variations in image grayscale range of the roots (Pfeifer et al., 2015). While there have been a number of studies on the relationship between the natural soil matrix and the roots that permeate it, these studies have tended to focus on aspects of soil architecture rather than the architecture of the root (e.g., soil macropores, soil pore space) (e.g. Hu et al., 2016; Kuka et al., 2013).

The aim of the present study is to investigate and compare the root architecture and root traits of the ten most dominant pioneer plant species of the forefield of Lys Glacier (NW Italian Alps) in their natural soil system by producing accurate 3D images of their root system using X-ray CT. The value of the X-ray CT is verified by comparing the obtained results with other commonly employed techniques. Moreover, root tensile strength measurements will be made to understand the biomechanical role of the plant species on soil stabilization. The retrieved information is discussed in the light of the potential future use of the studied species for slope soil reinforcement.

2. Materials and methods

2.1. Study site

Plant sampling was carried out on the recently deglaciated forefield of the Lys Glacier in the Aosta Valley (North West Italy). The glacial till was deposited in 2004 at an altitude of 2300 m above sea level on a bedrock of granitic gneiss and paragneiss belonging to the Monte Rosa nappe (D'Amico et al., 2014). The climate is alpine subatlantic with a mean annual rainfall of 1200 mm. The mean annual air temperature is −1 °C (Mercalli, 2003) with a winter temperature below −4 °C on average. The sampling site is south facing with a soil texture of loamy sand and a udic moisture regime (Soil Survey Staff, 2010). The chemical properties of the soil at the study site correspond to a slightly acidic soil (pH 5.8 – 6.7) with very low amounts of total nitrogen (TN) and total organic carbon (TOC) (0.002-0.017 g kg^{-1} and 0.018-0.217 g kg^{-1} respectively) with available phosphorus (P) of 1.3-4.7 mg kg^{-1} (Hudek et al., 2017). Pioneer alpine plants, mostly graminoid and forb species colonize the site (e.g., *Epilobium fleischeri* Hochst., *Linaria alpina* (L.) Mill., *Trisetum distichophyllum* (Vill.) P. Beauve.), a detailed vegetation survey of the moraine can be found in D'Amico et al. (2014).

2.2. Sampling approach

The ten most common plant species of the forefield were selected. These were sampled between August and September 2015: *E. fleischeri*, *T. distichophyllum*, *Trifolium pallescens* Schreb., *Luzula spicata* (L.) DC., *Silene exscapa* All., *Minuartia recurva* (All.) Schinz and Thell., *Festuca halleri* All. *Poa laxa* Haenke, *Salix helvetica* Vill. and *Leucanthemopsis alpina* (L.) Heyw (Table 1). A total of 60 soil columns, (i.e. 6 columns per species) were excavated. During sampling, special care was taken to avoid individuals with any visible