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Using the root spread information of pioneer plants to quantify their mitigation potential against shallow landslides and erosion in temperate humid climates

Alejandro Gonzalez-Ollauri*, Slobodan B. Mickovski

School of Engineering & Built Environment, Glasgow Caledonian University, Glasgow, Scotland, G4 0BA, United Kingdom

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ABSTRACT

The aim of this paper was to quantify the mitigation potential of pioneer herbs against shallow landslides and erosion in temperate humid climates and to identify key plant information to aid species selection for slope stabilisation. The objectives ranged from the study of the climate, soil and root spread of three native perennial herbs growing on a landslide-prone slope in Northeast Scotland to the verification of an upgraded spatially distributed eco-hydrological model in order to test whether root spread information can be provided cost-effectively in temperate humid climates. The retrieved information on root spread was then used to evaluate the slope stabilisation potential of the pioneer herbs in the topmost soil horizons using a limit equilibrium method.

The results indicated that pioneer herbs, although presenting climate-influenced shallow root systems, could noticeably contribute to reducing soil mass loss and landslides. This was largely determined by the plant biomass and allometry, the latter being a potential readily measurable proxy for species selection in slope stabilisation that will need further investigation. Additionally, our observations supported the model predictions remarkably well when site-specific inputs were employed, showing that the proposed model is a suitable and cost-effective tool to provide spatial root spread information for eco-engineering purposes in temperate humid climates.

1. Introduction

Landslides and erosion are a global hazard that lead to dramatic loss of human life, property and soil every year with an occurrence that will likely increase due to the effects of climate and land use change (van Beek et al., 2008; IPCC, 2014) if action is not taken.

The use of plants against shallow landslides and erosion has been shown to be an effective eco-engineering measure (Stokes et al., 2014) mainly provided by the soil-root mechanical reinforcement (Norris et al., 2008). A root-permeated soil makes up a composite material that has enhanced strength (Waldron, 1977), providing a similar effect to the soil like that of steel rods to reinforced concrete (Mickovski et al., 2009). However, to quantify the extent of soil-root reinforcement, information on the root spread in the soil is needed to evaluate the slope stabilisation potential of the plant in the topmost soil horizons.

Despite the relatively recent efforts to quantify root spread at a global scale (e.g. Schenk and Jackson, 2002; Schenk and Jackson, 2005), it still remains unknown for the vast majority of the wild plant species. Indeed, information related to pioneer herbs is severely scarce, as far more attention has been traditionally paid to woody plant species (Stokes et al., 2008) and crops (Böhm, 1979). Pioneer herbs may present a great eco-engineering potential as they are fast-growing, easily spreadable and set the basis for further ecological succession (Odum and Barrett, 1971). However, herb's root systems are expected to be limited to the topmost soil horizons, being more likely effective against rill or gully erosion (e.g. van Beek et al., 2008). Hence, the use of herbs in eco-engineering slope stabilisation actions needs to be combined with other remediation techniques (e.g. Tardio and Mickovski, 2016).

The root distribution in the soil may be complex and, obtaining related information is expensive and time-consuming. Thus, the development of numerical root distribution models has been the scope of research in the past few decades (e.g. Wu et al., 2005) and based on this research, for most practical eco-engineering applications, a root profile can be portrayed as a simple asymptotic mathematical function (Jackson et al., 1996). Additionally, it

* Corresponding author.
E-mail addresses: alejandro.ollauri@gcu.ac.uk, alejandro.gonzalez.ollauri@gmail.com (A. Gonzalez-Ollauri).

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has been observed that root spread is chiefly influenced by water availability in the soil (*i.e.* 'hydrotropism'; Darwin, 1880; Tsutsumi et al., 2003). This concept permits to link the root development to climate and soil properties (Schenk and Jackson, 2002) and, therefore, to the soil's water balance. In this sense, Laio et al. (2006) developed an analytical eco-hydrological model able to predict realistically the rooting depth at the plant community level for water-limited ecosystems (*i.e.* arid or dry environments) from readily available soil and climatic predictors. These predictors can be easily parameterised from the soil physicochemical properties (*i.e.* porosity, texture and organic matter content) and from temperature and rainfall information collected by many weather stations. However, the root spread has rarely been assessed using *in situ* soil and climate-derived information as data from distant meteorological stations and sampling locations are normally interpolated for a given study site (e.g. Preti et al., 2010; Tron et al., 2014). Laio's et al. model was further extended by Preti et al. (2010) to provide plant species-specific root profile information by the consideration of a universal property to all living organisms, the allometry (West et al., 1997). Plants allocate their biomass above and below the ground, and the proportion in which this is distributed can be assessed by the plant's allometric relationship (Cheng and Niklas, 2007) depicted by a simple power-law relationship (West et al., 1997). This relationship permits to cost-effectively infer the root biomass from measurements of the aboveground biomass and also potentially determine plant parameters related to soil reinforcement purposes (e.g. Hwang et al., 2015). To the best of our knowledge, the identification of plant indicators able to enhance the effectiveness of plant selection against shallow landslides has been rarely explored (e.g. Cornelini et al., 2008). Additionally, the existing models (Laio et al., 2006; Preti et al., 2010) are, essentially, one-dimensional and cannot be readily applied to temperate humid climates (Tron et al., 2014), which cover a big surface of the Earth (Köppen, 1884).

Climate, soil, and plant cover are spatially highly heterogeneous, which stresses the need of adopting spatial approaches to predict root system features under different environmental and landscape scenarios. However, spatially distributed root spread models are lacking in the literature (e.g. O'Brien et al., 2007; Coelho et al., 2003), although these types of models are very popular in hydrology and catchment science (Neitsch et al., 2011; Doppler et al., 2014). The development of distributed root spread models may be very helpful to assess the spatial effect of vegetation against shallow landslides and erosion or to enhance the predictive capacity of other spatial models aiming to quantify plant-derived processes (e.g. water fluxes, nutrient cycles or sediment dynamics at the catchment scale; SWAT; Neitsch et al., 2011). However, the performance of a given distributed model will rely on the quality of the spatial information used as an input. In this sense, the implementation of machine learning techniques, such as the *random forest* algorithm (RF; Breiman, 2001), for predicting spatially heterogeneous soil variables that drive root spread in the soil (e.g. soil water availability) may have great potential for providing spatial soil information cost-effectively (Malone, 2013). RF was conceived to produce accurate predictions that do not overfit the data (Breiman, 2001), it is more powerful than classical spatial interpolation methods (e.g. regression tree, universal kriging, cubist; Liess et al., 2012) and more interpretable than other machine learning techniques, such as neural networks (Prasad et al., 2006). The use of these techniques in environmental studies, although growing, is still poor.

The aim of this paper is to quantify the potential of pioneer herbs against shallow landslides and erosion in temperate humid climates and identify key plant information to aid species selection for slope stabilisation. To do so, we follow a step by step journey from the study of the climate, soil and the root spread of three native perennial herbs growing on a landslide-prone slope in Northeast Scotland, to the verification of our revised spatially distributed eco-hydrological model; testing whether root spread information can be provided cost-effectively in temperate humid climates. The retrieved information on root spread is then used to evaluate the pioneer herbs' slope's topmost horizons stabilisation potential using a limit equilibrium method, which outcome will contribute to shed light on key plant-related data for effective plant selection against shallow landslides and erosion.

2. Materials & methods

2.1. Study site

The study site lies within Catterline Bay, Northeastern Scotland, UK (WGS84 Long: −2.21 Lat: 56.90; Fig. 1), a region with mean annual temperature of 8.02 °C and mean annual rainfall of 1232 mm (UK Met Office, 2015); constituting a humid temperate climate site (Cfc: subpolar oceanic climate; Köppen, 1884). The precipitation is characterized by frequent, low-intensity rainfall events, while heavy storms seldom occur. The topography of the study site is dominated by sloped (25–50°) terrain and cliffs ending up into the sea, combined with a flatter inland area that is crossed by a small stream that leads to the formation of inclined river banks (Fig. 1). Shallow (ca. 600 mm) and well-drained soils can be found within the study area resting on top of sedimentary bedrock (*i.e.* conglomerate; BGS, 1999). The vegetation cover is dominated by herbaceous weeds and grasses, riparian trees and agricultural crops of wheat and barley. The sea has a limited influence on the vegetation as south-westerly winds prevail. Different soil mass wasting episodes (landslides and erosion) have been reported on the site in the past (e.g. Kincardineshire Observer 11/4/2013), mainly associated with prolonged rainfall periods. The failure zones are easily identifiable, presenting exposed bare ground or areas of sparse vegetation

2.2. Parameterisation

The parameterisation process was carried according to the diagram shown in Fig. 2 in order to identify and quantify the studied systems' elements governing plant root spread and feed a model aiming at providing root spread information in temperate humid climates (*i.e.* root profile distribution model, RPDM; see 2.3).

2.2.1. Climate parameters

Two types of climate data sets were employed: (1) short-term meteorological time series from a meteorological station located at the study site (2012–2014; vor de Poorte, 2015; Fig. 1; Point 1) (2) long-term meteorological time series belonging to 6 different weather stations located within the region of the study site (1996–2014; UK Met Office, 2015; Fig. 1; Points 2–7).

The growing season duration was determined according to the growing degree-days (GDD) approach (e.g. McMaster and Wilhelm, 1997). We assumed that the growing season started once the cumulative GDD reached 200 °C, and that root growth was inhibited when the daily air temperature was below 5 °C (Alvarez-Uria and Körner, 2007). The duration of the growing season was estimated for each station and year and then it was averaged for the considered time series.

The probability distribution of the rainfall intensity for each growing season was assessed by estimating and plotting its kernel density (Parzen, 1962) in R 3.1.2 (R Development Core Team, 2014). Then, the rainfall parameters λ_o (*i.e.* frequency of rainfall events) and α (*i.e.* mean rain intensity) were estimated for each growing season as indicated in Preti et al. (2010). Both parameters, λ_o and α, were averaged over the considered time series and compared against the values obtained at the study site's station prior