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RESEARCH ARTICLE

Impact of invasive plant control on soil loss: a case study on Robinson Crusoe Island

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Mechanical and chemical controls are the most common methods used to detain the advance of plant invasions. In some areas, clear-cutting of invasive plants produces soil loss, one of the worst impacts on ecosystems. It has been argued that cutting invasive plants in small areas with root retention could be an adequate control management strategy to deal with this problem. In this study, the soil loss in small gaps after cutting two invasive woody species with root retention is compared with the soil loss in the invasive surrounding scrubland. On Robinson Crusoe Island, 15 small canopy gaps of 36 m^2 were created in an area covered with invasive species. The gaps had three slope ranks including 15–20°, 20–25°, and 25–35°. Annual soil loss was measured both in these gaps and the invasive scrubland over 1 year with graduate erosion pins. In spite of the small size of clear-cutting areas, we found erosion to be severe, to extremely severe, after plant control with root retention inside the small gaps with slope ranks between 25 and 35°. On the other hand, in slopes less than 25° soil loss was similar in the small clear-cut gaps and invasive scrublands. Thus, we recommend precaution if the intention is to avoid erosion through clear-cutting control with root retention in fragile soils and slope areas, even in small areas.

Key words: clear-cutting, erosion, invasive species, Juan Fernández Archipelago, *Rubus* control

Implications for Practice

- We recommend clear-cutting with root retention of invasive species in small and low-slope areas.
- In areas with steeper slopes, however, additional measures should be taken to detain erosion until soil coverage with the desired species is achieved.

Introduction

Invasive plant species could have a negative, neutral, or positive effect on soil erosion in relation to native plants (Santos de Almeida 2013). When the effect of invasive plants on soil erosion is positive but, at the same time, they negatively affect the native biodiversity and other ecosystem services, decisions on whether to control these species or not, and how to do this, are very difficult.

Mechanical and chemical control of invasive woody plants is common practice in many countries (Buddenhagen 2006; Smith-Ramírez et al. 2017). Erosion rates are expected to increase immediately after invasive plants—or any plants—are cut, especially in areas with steep slopes and fragile soils (Bormann et al. 1968; Hajabbasi et al. 1997; Batten et al. 2005; Niklitschek 2015). Determining the most suitable area to harvest, or the number of trees to cut, has been one of the main topics in forestry studies over the last few decades (Borrelli et al. 2017). As a result of these studies, in addition to environmental concerns, clear-cutting areas for harvesting have been limited to a minimum of 8.1 ha in California, although other states of United States and other countries have not established limits (Niklitschek 2015). Another method of limiting clear-cutting has been to restrict the number of trees removed; in the protected forests of Russia, for example, only 10 trees/ha is permitted (Niklitschek 2015).

Clear-cutting can be used as a restoration tool, not just for extracting resources. In the case of clear-cutting of invasive species for restoration purposes, the objective is focused on biodiversity conservation; hence, the size of the cut-areas should be smaller than when clear-cutting for commercial purposes. Once the invasive species are cut, several years could pass, or even decades, before the cover of adult individuals planted will be able to protect the soil. In this scenario, one of the most common management recommendations to reduce soil loss after plant control is to keep the roots of invasive plants and clear-cut in small areas (NPS 2006). In spite of the fact that erosion after invasive plant control is a common issue in restoration projects, we found only one study measured this factor, which is Jien et al. (2015). However, in this case, the

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authors did not compare their results with a control that is uncut areas. We believe this comparison is important because the highly competitive invasive species often occur in areas that are undergoing a degradation and/or erosion process, even if it is not clear-cut.

This research was carried out on Robinson Crusoe (RC) Island, which has the fourth most invaded island forests, in relation to its surface area, reported worldwide (Smith-Ramírez et al. 2017). On RC Island, most of the invasive species are found on slopes ≥20° (Díaz 2013; Vargas et al. 2013). At present, small areas with invasive plants (130 m^2 on average) that were controlled at the end of the 1990s now have totally covered soil, mainly with native ferns and a giant herb (Vargas et al. 2013). However, areas controlled 5, 6, and even 7 years ago are still denuded, especially areas larger than 300 m^2. The aim of this study is to enrich the discussion about the benefits of keeping roots in small clear-cut areas located in different slopes, in order to avoid soil loss after cutting invasive species. Our first hypothesis is that small clear-cut areas avoid soil loss in spite of the increasing of slopes. The second hypothesis is that soil loss in small clear-cut areas is similar to that in invasive species scrubland. In this case, we compare our results with uncut areas that are in similar slopes to cut areas.

Methods

Study Area

RC Island is a small and steep island in the South-East Pacific. This island is part of Juan Fernández Archipelago, located 670 km west of the continent, facing the Valparaiso Region, Chile. This Archipelago is a National Park and Biosphere Reserve, and is a number one priority for conservation globally, or among the first 20 priorities, according to the different criteria of Environmental International NGO's (Durell Conservation Trust, World Wildlife Fund, and Bird Life International). It has also been considered as one of the two globally mini-hotspots (together with the Galapagos Archipelago), due to its high endemism per surface area and high threat status (Mittermeier et al. 1999). Besides, RC Island has 39% of its surface severe or severely eroded (Astudillo 2014). The RC Island forests have been heavily invaded and outcompeted mainly by three species of exotic species, *Rubus ulmifolius, Aristotelia chilensis*, and *Ugni molinae* (Arellano & Smith-Ramírez et al. 2016). These three invasive species account for 46.6% of the woody vegetation cover of RC Island (Díaz 2013).

The climate of RC Island, according to Köppen (Kottek et al. 2006), is Mediterranean oceanic, which presents a short, dry summer season (Marzol et al. 1996), with a high maritime influence. The only town on the island, San Juan Bautista, is located in Cumberland Bay, where the forest studied in this article is located. In Cumberland Bay, the annual average temperature is 15.3°C (Di Castri & Hajek 1976; Marzol et al. 1996) with an average annual rainfall of 1,023.7 mm during the period 1960–1994 (Marzol et al. 1996). Forty-four percent of annual rainfall occurs in winter (May–August), and only 9% in summer (November–February) (Marzol et al. 2001). The forests of this Bay also receive mist precipitations, which are highly frequent over 400 m.a.s.l. (Cereceda et al. 1994). The most frequent daily rainfall intensity in 12 hours in the period 1961–1994 was 1.0–9.9 mm (Marzol et al. 1996). However, on seven occasions, precipitations exceeded 100 mm in one day, and in the course of one year, this phenomenon occurred twice (Marzol et al. 1996). On one occasion occurred a maximum of 290.3 mm in 24 hours and 260 mm in 12 hours (Marzol et al. 1996). Over the last few years, hurricane winds have been reported once or twice per year in Cumberland Bay. San Juan Bautista town suffered some massive landslides due to the erosion of the surrounding hills, the worst of these occurring on 6 March 1972 and 12 May 1980, when woody material from the invasive shrubland was dragged into the town (Marzol et al. 1996). The highest hill surrounding the Bay (and the town) is El Yunque, reaching 900 m.a.s.l, whose ejection cones are rapidly crumbling as a result of deforestation of its slopes. Cumberland Bay is one of the biggest eroded catchments in the island, with an average erosion of 100 or 224 $t{\cdot}km^{-2}{\cdot}yr^{-1}$ (the variation depends on the model used) (Astudillo 2014). It is probable that the main effect of climate change in Cumberland Bay is an increase of wind storms, especially during "La Niña" years, as has been shown by the analysis of data over the period 1960–2012 (Kremer & Smith-Ramírez unpublished data).

There are no detailed studies of RC Island soils. In 1982, they were classified as of volcanic effusive (fisural) and explosive origin (eruptive). The soil of the study site was classified as "Mountain soil of incipient development derived from volcanic ash" (IREN-CORFO 1982). This soil type is thin, affected by a continuous and permanent process of weathering of parental material making it fragile and showing laminar erosion in areas with pronounced slopes (IREN-CORFO 1982). Given that this soil type is covered by forests, it is considered less erosive than the other two soil types (IREN-CORFO 1982). Specifically, in our study site the soil has been described as shallow, with pH = 6.0, organic material = 20.02%, well drained, with a silty loam texture (Castro & Merlet 2015).

Experimental Design

Usually, the term clear-cut is used to refer to areas ≥5 ha (Keenan & Kimmins 1993); however, we decided to use this term, to contribute to the discussion of this topic, in small areas destined for biodiversity conservation. We chose a very conservative gap size to clear-cut invasive species (0.0036 ha), in order to avoid producing too much soil loss. In autumn 2010, 15 circular gaps of 6-m diameter each were created within an area invaded mainly by *Rubus* and secondarily by *Aristotelia* (a small Elaeocarpaceae tree). These gaps were located at 250 m.a.s.l. at the edge of the native forest called Plazoleta El Yunque on RC Island. This forest and the invasive scrubland that surrounds it are at the base of the El Yunque hill. The exotic species in each gap were completely cut at the base of the stumps using brush-cutting and chainsaw. On average 1.6 *Aristotelia* and 38.6 *Rubus* were cut per gap; the stumps had a height of around 15 and 9 cm for *Aristotelia* and *Rubus*, respectively. A herbicide (Triclopyr) was applied by contact to prevent resprouting. The roots were kept so as to provide soil resistance to the continuous erosion produced by the collapse of the hill. The scrubland gaps were created in three slope areas, with the rankings low (15–20°, 3 gaps), medium (20–25°, 6 gaps), and high (25–35°, 6 gaps). The distance among gaps was around 20–100 m.

The erosion pins method was used in order to evaluate soil erosion in gaps after invasive plant removal (Haigh 1977; Hudson 1993, 1995). To determine the height of soil loss by erosion, a total of 180 iron pins of approximately 30 cm length were installed in gaps and invasive scrubland. The pins were buried 10 cm into the ground down to the level of a mark on the pin. Six iron pins were randomly established in each gap and, as a control, another six pins were established in the *Aristotelia* and *Rubus* scrubland surrounding the upper portion of each gap, so that the eroded soil in the gap would not affect the soil erosion measurements in the scrubland. The pins were installed regularly in each gap and scrubland, and were not moved throughout the duration of the study. The distance between the pins in the scrubland to the gap border was around 1–1.5 m. Logistically it was difficult to install pins further from the border because invasive plant coverage was 100%, and it was impossible to circulate without removing the invasive plants. Following other quantitative studies of soil loss (Ghimire et al. 2013; Li et al. 2016), we did not set up borders around each gap. However, we assume that the dense vegetation around each gap avoids the soil loss that can be dragged by the rain to some neighboring microbasin. Every 4 months (after winter, spring–summer, and summer–autumn), the height of soil loss by erosion (Y), corresponding to the distance between the pin mark and the current surface of the soil, was measured with a small graduate ruler. The assay was maintained over 1 year.

We quantified soil loss in each gap using the following formula: $X(\text{g}) = Y \times A \times \text{BD}$, where X is the amount of soil loss by erosion, Y is the height of soil loss (cm), A is the gap area (cm^2), and BD is the bulk density (g/cm^3), corresponding to the relationship between the weight of dry soil (weight of the solid phase) and the volume it occupies including porosity, that is the volume of undisturbed soil. The BD was calculated as follows: P_s/V, where P_s is the weight of the dry soil (g) and V is the volume of the soil sample (cm^3). To evaluate the apparent density of the soil (BD, g/cm^3) in each gap and the surrounding scrubland, four random soil samples were taken at the surface level. The superficial soil samples were taken with a cylinder from the top 5 cm of soil. The cylinder had a volume of 62.8 cm^3. The soil samples were transported in paper bags to a laboratory on RC Island, where the soil was dried in an oven at 120°C for 24 hours and then weighed to obtain P_s. This measurement was performed at the beginning of the experiment, and subsequently the soil samples were returned to their place of origin.

The bulk density found was low, on average 0.49 ± 0.03 g/cm^3 ($X \pm$ SE), minimum value was 0.32 g/cm^3, and maximum value was 0.75 g/cm^3. The low BD could be explained due to the high organic matter content of the soil (Crain 2013; Castro & Merlet 2015).

Table 1. Height of eroded soil in gaps and invasive scrublands in Robinson Crusoe Island, according to the slope range after 1 year of sampling (*X*, mean; SD, standard deviation).

	Gap		*Scrubland*	
	Eroded height (cm/yr)		*Eroded height (cm/yr)*	
Slope	X	*SD*	X	*SD*
15–20°	0.88	0.75	1.36	0.59
20–25°	1.20	1.08	1.00	0.64
25–35°	1.91	1.17	0.99	1.09

Statistical Analyses

In order to evaluate whether the removal of invasive species and the slope affected soil loss, a two-way analysis of variance (ANOVA) was performed, where the dependent variable was the amount of soil loss (g) one year later, and the factors (or independent variables) were the environment (gap and scrubland) and slope (15–20°, 20–25°, and 25–35°). In order to evaluate if there had been an accumulative effect of time (4, 8, and 12 months) on soil loss, a repeat ANOVA was performed. All data had a normal distribution. When the ANOVA result was significant, a post hoc test was carried out (Tukey's honest significant difference [HSD] test). The analyses were performed with an accuracy level of 95% using the statistical program Statistica (StatSoft Inc., Tulsa, Oklahoma, USA).

Results

The highest average values of eroded soil and soil loss after one year were in gaps with a slope range above 25° (Table 1; Fig. 1), followed by gaps with a slope range between 20 and 25°. The amount of total soil loss did not vary significantly between environments (gap and scrubland: ANOVA $F_{[2,16]} = 2.477$, $p = 0.135$), whereas the amount of soil loss in soils with slopes over 25° was significantly higher than in soils with lesser slopes. (ANOVA $F_{[2,16]} = 4.598$, $p = 0.026$, Tukey's HSD test, $p < 0.035$). The interaction between environment and slope was significant (ANOVA $F_{[2,16]} = 6.424$, $p = 0.009$). Specifically, the soil loss in gaps over 25° was significantly higher than the values obtained in the lower slopes (10–20° and 20–25°, Tukey's HSD test, $p < 0.03$, Fig. 1). In contrast to clear-cutting areas, soil loss in the invasive scrubland remained relatively uniform and there were no significant differences when comparing the three slope conditions (Tukey's HSD test, $p > 0.9$).

When comparing the soil loss between the two conditions (clear-cut gaps and invasive scrubland), it was found that soil loss was only significantly higher in gaps than in scrub in 25–35° slopes (Tukey's HSD test, $p < 0.007$, Fig. 1). In the other two slope conditions, these differences were not significant (Tukey's HSD test, $p > 0.8$, Fig. 1). Soil loss did not vary

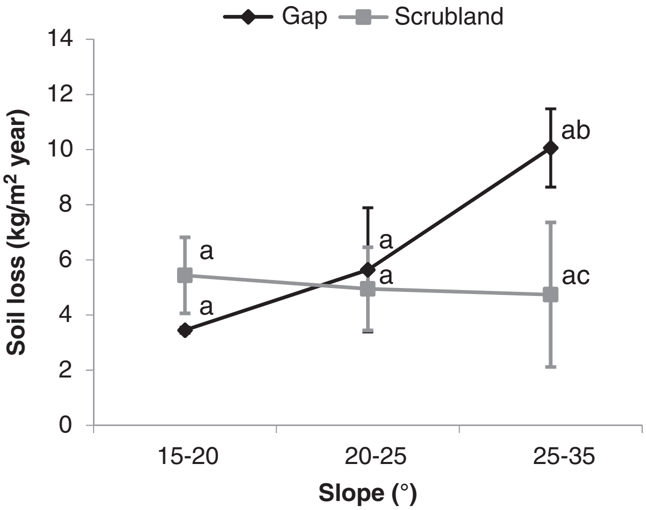

Figure 1. Soil loss ($kg \cdot m^{-2} \cdot yr^{-1}$) in gaps and invasive scrublands in Robinson Crusoe Island, according to slope range (mean ± SD). Different letters indicate significant differences in the interaction between environment and slope. Means followed by the same letter are not different.

significantly in the different seasons studied (Tukey's HSD test, $p > 0.2$).

Discussion

During 15 years, invasive woody plants have been cut in mainly small gaps (from 100 to 160 m^2) in the middle of the Plazoleta El Yunque forest on RC Island. However, on occasions gaps of 700 m^2, or even as big as 1.700 m^2, have been cut on slopes exceeding 30°. These management measures include the root retention of *Rubus* and *Aristotelia*. We recommend caution with this type of management because even in the small experimental gaps of 3.6% of hectare, the erosion produced by the control of invasive species could be extremely severe (scaling up the data according to FAO standards of 1980) in areas with more than a 25° slope. Based on our results, we reject the first hypothesis that in small clear-cut areas the roots of invasive-species stumps avoid soil loss, in spite of increasing slopes. We only partially accept our second hypothesis, because we found the same soil loss in small denuded areas as in the invasive scrubland in slopes below 25°, but not when the slope increased.

The results of this study show that even small areas are prone to erosion after removal of exotic species by cutting on RC Island. Our results concur with Jien et al. (2015) who found that one year after the invasive woody species, *Leucana leucocephala,* on Taiwan Island was removed, severe and even extremely severe soil loss occurred. In this case, the experimental area was 2.2 ha, with a 5% slope, the soils ranged from sandy loam to silt clay and the precipitation per year was 1.800 to 2.000 mm. Jien et al. (2015) also found that the soil loss affected the establishment of some native species planted after the *L. leucocephala*'s stand was cut. We concur also with D'Antonio and Meyerson (2002) who proposed that after invasion, the removal of the exotics might cause further erosion, especially if there is a time-lag between removal and desirable plant establishment.

Other authors have come to a different conclusion after control of invasive species. For example, after the treatment of the *Urochloa maxima* (Guinea grass) in Buck Island Reef, a U.S. National Monument, in one year with heavy rainfall, the authors believed that the persistence of the radical Guinea grass system provided enough soil stabilization (NPS 2006), avoiding erosion. It is reported also that three exotic species, *Lygodium microphyllum, Schinus terebinthifolius*, and *Sansevieria hyacinthoides*, in the Big Cypress National Reserve and Everglades National Park did not produce erosion after control (NPS 2006). In none of these cases was quantitative information given in their reports (NPS 2006).

Rubus on RC Island has an unusually high aerial biomass (in comparison with other *Rubus* species), with a woody trunk that can reach a diameter of 15 cm at the base and a height of up to four or more meters; it was also reasonable to expect high root biomass and high soil retention capability. Nevertheless, the conclusions of our study show that erosion is high on steep slopes, in spite of root retention of invasive species and the small size of cutting areas. However, erosion could be considered acceptable in cutting areas with less than 15° slopes and does not differ from that of invasive shrubland in areas with less than 25° slopes. On Crusoe Island, where invasive species occur in areas with slopes over 20°, it is necessary to control it using additional management techniques. We propose using mulch, or by planting desirable fast-growth species that, in this case, could be native ferns and giant herbs (*Gunnera* spp.). In plant control assays where soil loss is expected after cutting or removing, we recommend monitoring soil levels and intervening in order to prevent high soil loss. Finally, we recommend further studies be undertaken comparing soil loss in clear-cutting areas with soil loss in areas covered by invasive species. This comparison is important because the degraded lands usually preferred by invasive species could still be undergoing an active erosion process, even in the presence of these species.

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