Research article

Fruit provision from *Berberis microphylla* shrubs as ecosystem service in *Nothofagus* forest of Tierra del Fuego

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ABSTRACT

Berry production is a non-wood product worldwide recognized by its nutritional value and taste, but the most studied species are non-native commercial plants in productive areas, leaving aside native berries. We propose that native berries (*Berberis microphylla* G.Forst) naturally growing in degradation forests areas could diversify livestock establishment production and complement traditional uses (e.g., livestock). The aims of this work were to 1) environmentally characterize (e.g., soil nutrient content and physical conditions, air conditions and photosynthetically active radiation) in three degraded *Nothofagus antarctica* Oerst. forest (due to past fires and livestock use) of Tierra del Fuego; and 2) evaluate berries production of *B. microphylla* in terms of quality production (e.g., fruit number and weigh per shrub) and in terms of quality (individual fruit weight, fruit pulp percentage, and soluble solids content) to assess provisioning ecosystem service of this native shrub in different degraded areas. Studied sites were defined as: 1) *Severe soil degradation condition (SEV)* (high frequency of horses, bulls and some native guanacos year round, severe soil erosion, and shorter herbaceous layer), 2) *Moderate soil degradation condition* (MOD) (cattle and guanaco year round, intermediate level of soil erosion and intermediate height of herbaceous layer), and 3) *Slight soil degradation condition* (SLI) (livestock only during winter, but high frequency of native guanacos, lower soil erosion and taller herbaceous layer). (SEV) had the highest air and soil temperature, least soils nutrients content, highest bulk density, the least soil water content and the poorest fruit production. (MOD) had the highest soil water content and nutrient-rich soils, while (SLI) had the highest relative air humidity and PAR. *B. microphylla* shrubs grow with similar morphology on the different soil degraded condition. The highest fruit production were at (SLI), however the (SEV) had the highest soluble solids. We conclude that calafate shrubs in degraded *Nothofagus* forests offer a provisioning ecosystem service through their excellent fruits quality. Livestock farms could diversify their production through native fruits taking advantage of the altered areas occupied by *B. microphylla*. However, we recommend avoiding intensive livestock use in burned forests since it could lead to an irreversible soil erosion. Proper livestock management in *Nothofagus* burned forest could keep over the time not only the recognized ecosystem provision services (fruits, meat, wood), but also those of regulation and support that calafate shrubs offer and that make the functionality of the ecosystem.

1. Introduction

Ecosystem Services (ES) are goods and services offered by natural habitats that benefit human beings (Valdez and Luna, 2012). ES assessments are also crucial for economic development and for the social well-being (Constanza et al., 1997; Boudell, 2018; Lipton et al., 2018). Among ES classification (Fisher et al., 2009), provisioning ES satisfies

what a consumer needs, and it has been studied extensively with the objective of enhancing local food supplies (Collins et al., 2010).

Non-wood forest products, such as the so-called group of minor or underutilized fruit species (Tacón Clavaín, 2004), are relevant for the diversification of food production and are recognized as a provision ES provided by terrestrial ecosystems. The incorporation of native berry plants in agroforestry systems, stimulates the diversification of products, while benefiting local biodiversity, and promote adaptation to global

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changes. Furthermore, the use of native plants as part of local food production can help to develop more sustainable agriculture (Shelef et al., 2017). This takes special relevance in places where fruiting plant species grow naturally after anthropic disturbances. In Patagonia, it is common to observe forest landscapes recolonized by fruiting shrubs after fires or extensive livestock impacts (Kitzberger et al., 2005; Mermoz et al., 2005).

In Tierra del Fuego Island, native forests cover approximately 35% of the surface, which represent one of the most important genuine resources of the region (Collado, 2001). The so-called Ecotone Zone is dominated by *Nothofagus antarctica* Oerst. (ñire) forests. This tree species is the one with the greatest ecological adaptability to environmental conditions within the *Nothofagus* genus, as it presents different morphotypes (from bushy and branchy <5 m tall, to tree-like reaching 20 m tall in most suitable sites) (Donoso and Steinke, 2006; Allué et al., 2010). In these forests, 70% of area has been used for livestock production for the last 100 years (Ormaechea, 2012). Consequently, some of the most recognized provision ES are natural fodder for meat production and wood extraction for firewood and poles (Reque et al., 2007; Peri et al., 2016; Ormaechea et al., 2010). However, other provision ES arise from the natural coexistence of *N. antarctica* and *Berberis microphylla* (Luebert and Pliscoff, 2006), which usually is neglected as part of these forest ecosystem.

Berberis microphylla G.Forst, known as "Calafate", is a typical native shrub of Patagonia, and in Argentina, it grows from Neuquén to Tierra del Fuego (Orsi, 1984). It is an erect, thorny evergreen shrub, height maximum of 4 m, which inhabits open areas, grasslands, and rivers (Moore, 1983). The shrubs have been locally recognized by the fruit that looks similar to blueberry. This berry has the highest sugar content (14.6%) compared to other fruits such as cherry (9.9%), strawberry (5.5%), blueberries (6%), raspberry (4.8%) and blackcurrant (5%) (Arena et al., 2013). It has an antioxidant capacity 10 times greater than apple, orange, and pear fruit and 4 times greater than that of blueberry (Rodoni et al., 2014). Currently, commercial berry orchards are recommended due to their economic potential related to the flavor, taste, and nutraceutical properties of fruit (Giordani et al., 2017).

Although native plants have agronomic potential and adaptive capacity (e.g., to local soil conditions and climate of natural areas), it is expecting that the fruit production change with the different growing conditions. The advantage of native species is that they are adapted to local environmental variability, so they can grow and reproduce without much investment (Mostacero et al., 2017). Nevertheless, the most studied and used fruit for commercial purposes are exotic species (Vega González, 2013).

While most of the commercial plants were genetically improved, the productivity can also vary with different climatic and soil conditions. For example, variability in cloud cover can produce instability in blueberry yield (Petridis et al., 2018) because the flower bud number had a close relationship with the light condition (Yáñez et al., 2009). On the other hand, high temperatures in the flowering phase affect the pollen tube growth and degenerate the ovule, which leads to a reduction in fruit formation (Yang et al., 2019). Regarding soil nutrients, previous studies have shown that blueberries respond to nitrogen additions in almost all regions where they have grown (Hanson, 2004). Potassium improves the fruiting yield because it increases the efficiency in the use of water and the resistance to stress condition (Morales, 2017). Nitrogen and potassium fertilization improve fruit weight and increase the total soluble solids (Jiao et al., 2017). Soils with high organic matter content, promote the characteristics of the desirable fruit (Jiafeng et al., 2019). All these environmental variables are closely related. For example, organic matter content is affected by the temperature and soil humidity conditions, and pH, among others (Strahm and Harrison, 2008). In this sense, the challenge is to determine which environmental characteristics maximize fruit production and quality.

The growing demand for berries such as blueberry, raspberry, and others including native berries, is estimated at an annual growth rate of almost 6% projected by 2023 according to the global market trends (Pino et al., 2019). In Patagonia, there is a growing interest in native berries of *B. microphylla* as commercial local food. Whereas *B. microphylla* is a characteristic shrub of terrestrial ecosystems in Patagonia including burned forests, grasslands, and other degraded areas (Silva, 2013), this study can contribute to revaluing degraded sites through the supply of non-wood forest products. The aims of this work were to 1) environmentally characterize (soil temperature, soil water content, soil nutrient content, pH, soil texture, bulk density, air temperature, relative air humidity and photosynthetically active radiation) three soil degraded forest (due to past fires and livestock use) in Tierra del Fuego; and 2) evaluate the berries production of *B. microphylla* in terms of quality (fruit number, fruit weight per shrub and percentage of sound fruit) and quality (individual fruit weight, seed number, percentage of fruit water, pulp, seed, and soluble solids contents) to assess provisioning ecosystem service of this native shrub in the different soil degradation conditions.

2. Materials and methods

2.1. Study area description, climatic and soil parameters

The study was carried out in the forest area of central-east of Tierra del Fuego, Argentina, dominated by *Nothofagus antarctica* G. Forst. Oerst forests (Figure 1). These forests were affected by fire more than eighty years ago reducing the canopy cover (22.6%) and tree density (47–209 ind.ha^{-1} of trees >10 cm DAP) compared to undisturbed forests in the area (60–70% and 400–550 ind.ha^{-1}, respectively according to Soler and Peri, 2018). Furthermore, forage species (e.g., *Holcus lanatus*, *Dactylis glomerata*, *Poa pratensis*, *Trifolium repens*) were sowed after fires to improve natural pastures for livestock, altering or replacing the natural composition of herbaceous understory. Anthropogenic forest fire added to grazing and trampling domestic cattle is a recognized type of disturbance Tierra del Fuego, characterized by abundant forest legacy necromass on the ground (Frangi et al., 2004). The post-disturbance dynamic of woody vegetation -including tree regeneration- and permanent grazing have led to conversion of forestlands into shrublands where *Berberis microphylla* dominates the woody layer. Therefore, all selected study sites express degradation in terms of both, the vertical structure (height, mature basal area, canopy cover) and the specific composition of plant communities that support ecosystem functions. Currently, these sites continue to be used for livestock (cattle and domestic horses) with different stocking densities (in addition to free use by guanacos) and seasonal summer-winter movements. In addition to evident alteration of forest structure, it is possible to recognize different soil degradation levels related to the intensity of use of each site. Under this scenario, we selected three degraded areas (18–125 ha in size, separated approximately by 4 km from each other) defined as: A) *Severe soil degradation condition:* heavy grazing due to high frequency of horses (90 feces ha^{-1}), bulls (317 feces ha^{-1}) and some native guanacos (65 feces ha^{-1}) year round, with evidence of severe soil erosion (12.1% of bare soil), and shorter herbaceous layer (13.9 cm). B) *Moderate soil degradation condition:* high frequency of cattle (515 feces ha^{-1}) and guanacos (240 feces ha^{-1}) year round, evidence of intermediate level of soil erosion (1.8%), and intermediate height of herbaceous layer (16.3 cm). C) *Slight soil degradation condition:* light grazing due to use by livestock only during winter (311 feces ha^{-1}), but high frequency of native guanacos (325 feces ha^{-1}), lower evidence of soil erosion (1.3%) and taller herbaceous layer (19.0 cm). Three replicates separated approximately by 0.6 km were selected for each degradation condition, and 10 shrubs were randomly selected for subsequent analyzes in each repetition (n = 30 shrub per degradation condition).

Microclimate variables (air and soil temperatures and relative air humidity) were registered daily and every 60 min by three data loggers (HOBO 88K, Onset, USA) at each degradation condition (n = 3 per condition). The soil temperature sensor was placed 10 cm deep and the air temperature sensor at 60 cm from the ground during the growing
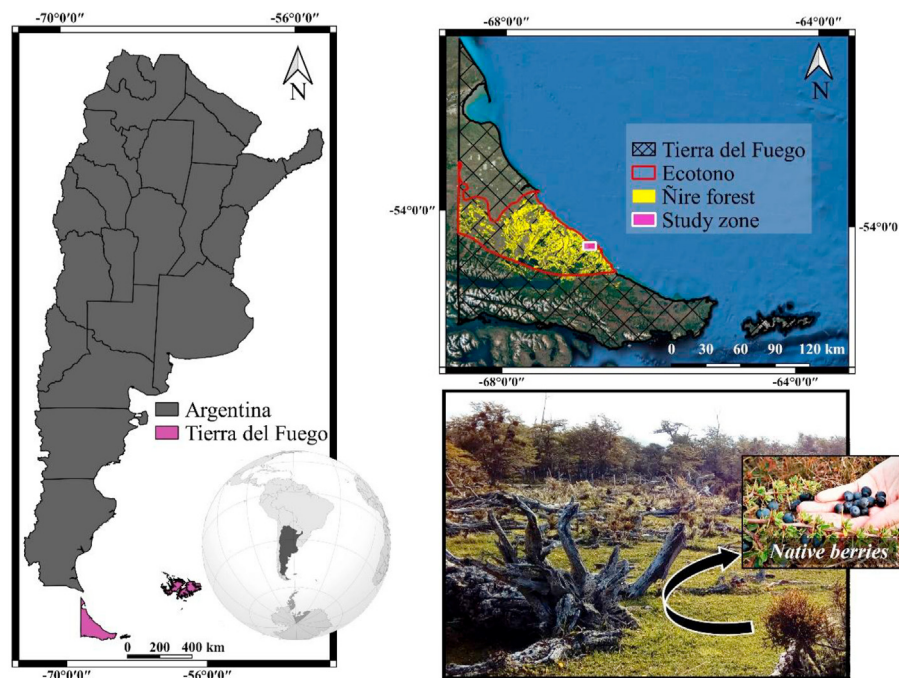
Figure 1. Study zone located at the center of Tierra del Fuego Island, Argentina. Left: map of Argentina; Right upper: *Nothofagus antarctica* forest distribution within the Ecotono area of Tierra del Fuego, indicating the study area (violet square); Right below: landscape under study.

season (November–December 2018 and January–February 2019). Soil water content measurements were taken by an MP406 moisture probe (ICT, Australia) at 10 cm depth at each shrub (n = 30 per condition). In addition, photosynthetically active radiation (PAR) was measured near each shrub with a digital ceptometer (Decagon AccuPAR LP-80) at the soil level (n = 30 per condition).

Soil samples were taken in each shrub (n = 30 per condition) by a cylinder (184.7 cm^3) at 5 cm of depth near shrubs removing the dense network of fine grass roots to avoid plant content in the sample. Soil samples were dried in an oven at 70 °C, before weighing on a precision balance (±0.0001 g). Bulk density for each shrub was calculated as the relationship between the obtained dry weight (g) and the corresponding cylinder volume (cm^3) (n = 30 per condition). Soil texture was determined by using a particle size analyzer Mastersizer 2000E Malvern at CADIC (n = 30 per condition). For nutrient contents and pH, the soil samples were first sieved by a 2 mm mesh and then pooled in two composite samples per replicate (n = 18). pH measurements were calculated by mixing 10 g of soils with 25 ml of water leaving a reaction time of 10 min (Guitián and Carballas, 1976) using pH meter (GLP 21 Crison). The nitrogen and phosphorus contents were determined with an AA3 AutoAnalyzer after performing a micro Kjeldahl digestion (Castro et al., 1990). Potassium and magnesium were obtained by VARIAN Atomic Absorption Spectrophotometer FS. Total carbon was determined by oxidation with potassium dichromate in an acid medium and Mohr's salt, following the method of Saverlandt (Guitián and Carballas, 1976). The amount of organic matter was obtained by multiplying the amount of carbon by the Van Bemmelen factor (1.724). Chemical analyses were conducted at the University of Santiago de Compostela.

2.2. Shrub measurements and fruit production

Shrub morphology (height, maximum diameter, and minimum diameter) was measured for each plant, and the shrub volume was estimated by ellipse formula (2/3*π*height*(maximum diameter/2*minimum diameter/2)).

The shrub productivity was evaluated in two successive summers (February 2018 and 2019). To estimate the fruit production in terms of

quantity we measured: total fruit number, total sound fruit (no damaged by insects, birds or fungi) and total fruit weight were measured for each shrub, and then these variables were weighted by shrub volume. To estimate the fruit production in terms of quantity a fruit sample (12 sound fruits per condition) was pooled by each repetition to analyze per fruit: fresh weight, dry weight (the fruits were dried in an oven at 60 °C until constant weight), seed number and dry seed weight. Soluble solids were determined at each soil degradation condition by a pool of fruit extracting the fruit juice by using an Atago N1 alpha refractometer (0–32 °Brix measurement range) (n = 18).

2.3. Statistical analysis

We verified the data distribution of our variables and the normality assumption by the Shapiro-Wilk test. The climate, environmental data and soil properties did not match those for a normal distribution and were analyzed with Kruskall Wallis considering the degradation soil condition as main factor. The procedure used to judge the significance of comparisons is the one described in Conover (1999). To determine the most prevalent morphological characteristics of *B. microphylla* shrubs, we classified the absolute and relative frequency of shrub height and diameters. Fruit production variables were analyzed with Kruskall Wallis considering the degradation soil condition as main factor (p < 0.05). For all analyses, the statistical software InfoStat (Di Rienzo et al., 2012) was used. Moreover, a principal component analysis (PCA) was done using a matrix of climatic, environmental and soil variables to understand the combination of factors that contribute to explain the difference among the degradation conditions. PC-ORD software was used for PCA.

3. Results

3.1. Area description, climatic and soil parameters

Mean air temperature varied among degradation conditions, as it was higher in Severe (10.7 °C) compared to Moderate (9.7 °C) and Slight (9.7 °C) (p < 0.001; Table 1) during the 2018–2019 growing season. Soil temperature was lower in Moderate (10.2 °C) compared to Severe (11.7

°C) and Slight degradation condition (11.5 °C) (p < 0.001; Table 1). The relative air humidity was significantly lower in Severe (52.7 %) followed by Moderate (62.2 %) and Slight (66.4 %) (p < 0.001 Table 1). In addition, soil water content, PAR, and bulk density differed among degradation conditions (Table 2). Soil water content was significantly higher in Moderate, while PAR was significantly higher in Slight, and the bulk soil density was higher in Severe compared to the other conditions.

Regarding chemical soil properties (Table 3), Slight and Moderate soils were more acid than the Severe condition. Organic matter content in Moderate was similar to Slight, but it duplicates the content in Severe. The highest macronutrient contents were found in the Moderate, while the Severe condition showed the lowest values. C/N ratio was similar among the three degradation conditions. Regarding soil texture (Table 4), all conditions were sandy loam according to the classification used by the U.S. Department of Agriculture. However, the degradation conditions had a significant effect on soil texture, where Severe had sandier and less loamy soils than the other conditions.

When these variables were analyzed through a principal component analysis (PCA) (Figure 2), the axis 1 (54.9 % of explained variance) was mainly negatively correlated with air temperature (-0.9142), and positively correlated with carbon and organic matter (0.9017). This axis separated the different sites into defined groups. The severe soil degradation site with less carbon and organic matter and higher air temperature was grouped on the left side. On the right side the Slight degradation soil site was grouped with opposite characteristics (higher carbon and organic matter and lower air temperature). It was observed that the Slight degradation soil site was closer to the Moderate degradation soil site indicating that these sites were similar in the mentioned variables. The axis 2 (19.1 % of explained variance) was mainly negatively correlated with C/N ratio (-0.8822) and to a lesser extent was negatively correlated with relative humidity (-0.6062). This axis showed that the most productive site was separated from the other sites mainly by its higher C/N ratio and, to a lesser extent, by its higher relative humidity.

3.2. Shrub characterization and fruit production

Berberis microphylla shrubs had a mean height of 0.83 m (varying among 0.4–1.4 m), a mean maximum diameter of 1.47 m (varying among 0.6–3.0 m) and a mean minimum diameter of 1.17 m (varying among 0.4–2.2 m). In Severe and Moderate, approximately half of the shrubs are concentrated in similar morphological measures. Slight showed more distributed frequencies of shrub height (Table 5). However, only significant differences were found in the minimum diameter (H = 749; p = 0.023) being lower in Severe (1.04 m), followed by Moderate (1.17 m), and by Slight condition (1.30 m).

Fruit number and weight (per shrub and shrub volume) was significantly affected by the different soil degradation condition. Fruit number and weight were highest in Slight soil condition, and these values doubled the production of Moderate, and tenfold that of Severe soil condition. Respect sound fruits, although the most degradation site had the lowest percentage of sound fruits, no significant differences were found in the different soil degradation condition (Table 6).

The degradation condition also affected the individual fruit characteristics. Slight had higher values of individual fresh fruit weight, dry fruit weight, seed number per fruit and dry seed weight. Regarding fruit quality, Severe soil degradation condition produced fruits with the lowest water content, the highest pulp proportion, and the highest soluble solids. Moderate degradation soil condition had similar values of water content and pulp, but significantly lowest soluble solids. In contrast, the Moderate site was the one with significant highest water content and significant lowest pulp content with an intermediate soluble solid value. The proportion of seed weight did not vary among degradation conditions (Table 7).

4. Discussion

Berberis microphylla shrubs grow with a similar morphology on a wide range of livestock management in burned *Nothofagus antarctica* which show its great adaptive capacity (Bottini et al., 2000). The natural ability to propagate by rhizomes belowground, the regrowth capacity post-disturbance, as well as mechanical defenses (i.e., thorns) make it a resistant shrub and capable of occupying heavily altered sites. This advantage has also been recognized in other shorter multi-stemmed shrubs, which dominates early regrowth after fire (Müller et al., 2007).

The soil degradation categories defined at the beginning of this study were confirmed with the soil bulk density values. In this sense, it can be stated that soil compaction in burned Patagonia forest is directly related with different animal management. Trampling damages reduces vegetation cover, soil water infiltration (Dunne et al., 2011) and prevents the root development of shrub and woody species (Cuenca Piso, 2014). These could explain calafate shrubs with smaller diameter at Severe degradation soil condition considering that these factors limit plant growth (Xu et al., 2013). High stocking rate could also limit branch expansion through herbivory damage considering that calafate is within the group of species that are mostly consumed when there are scarce resources (Soler et al., 2012).

On the other hand, considering that the transit and trampling of animals mainly affect soil texture (Medina, 2016), the highest percentage of sand in the Severe soil degradation condition evidence an erosive soil process (Rojas et al., 2013). Soil erosion is considered an irreversible process of habitat degradation, which causes changes in texture and nutrient content (Aimar et al., 2011).

Respect soil nutrients, the poorest soil nutrient content coincides with the most Severe degradation condition, but Slight and Moderate soil degradation condition were some unexpected. The highest soil nutrients in Moderate soil degradation condition could be a consequence of more remnant trees after fire (209 trees ha-1) (unpublished data) compared to the other sites (47 and 112 trees ha-1 in Severe and Slight, respectively) since tree canopies modify soil properties and cycles (Finzi et al., 1998; Falcón, 2002). Bahamonde et al. (2013) proved that the soil nutrient content was directly related with forest litter in South Patagonia. The lower soil carbon concentration compared to other values informed for *B. microphylla* shrub lands near to our study sites (8%, Arena et al., 2003) was related to the fire effect on soils (e.g., organic layer burned, lack of tree litter input) (Mansilla et al., 2014). On the other hand the lowest soil

Table 1. Mean values (±EE) of A) air temperature (°C), B) soil temperature (C°), and C) relative air humidity (%) for each degradation soil conditions (Severe, Moderate, Slight) during the growing season 2018–2019 (n = 3).

Condition	Air temperature	Soil temperature	Relative air humidity
Severe	10.72 ± 0.27 b	11.68 ± 0.20 b	52.74 ± 0.86 a
Moderate	9.76 ± 0.25 a	10.20 ± 0.17 a	62.31 ± 1.03 b
Slight	9.76 ± 0.89 a	11.51 ± 0.16 b	66.4 ± 0.99 c
H	*23.94*	*38.49*	*90.27*
p	*0.0120*	*<0.0001*	*<0.0001*

Different letters in each column indicate significant differences (*p < 0.05*).

Table 2. Mean values (±EE) of soil water content (SWC) (%), bulk density (BD) (gr/cm^3), and photosynthetically active radiation (PAR) (μmol m^2 s^{-1}) for each degradation soil conditions (Severe, Moderate, Slight) (n = 30).

Condition	SWC	BD	PAR
Severe	8.78 ± 0.51 a	0.93 ± 0.0020 b	792.24 ± 7.15 a
Moderate	11.03 ± 0.53 b	0.67 ± 0.0018 a	1025.01b ± 31.45 b
Slight	9.56 ± 0.54 a	0.62 ± 0.0024 a	1103.55 ± 11.85 c
H	*12.41*	*50.17*	*62.26*
p	*0.002*	*<0.0001*	*<0.0001*

Different letters in each column indicate significant differences (*p < 0.05*).

Table 3. Mean values (±EE) of soil chemical properties (potential hydrogen (pH), organic matter (OM) (%), carbon (C) (%), nitrogen (N) (%), C/N ratio (C/N), phosphorus (P) (%), potassium (K) (%) and magnesium (Mg) (%)for each degradation soil conditions (Severe, Moderate, Slight) (n = 6).

Condition	pH	OM	C	N	C/N	P	K	Mg
Severe	5.4 ± 0.03 b	5.1 ± 0.25 a	2.9 ± 0.14 a	0.2 ± 0.04 a	14.6 ± 2.79	0.06 ± 0.01 a	0.6 ± 0.03 a	0.6 ± 0.08 a
Moderate	5.1 ± 0.09 a	10.8 ± 1.44 b	6.3 ± 0.84 b	0.5 ± 0.04 b	11.9 ± 1.38	0.12 ± 0.01 b	0.8 ± 0.01 b	1.9 ± 0.05 c
Slight	5.2 ± 0.04 ab	8.9 ± 0.34 b	5.2 ± 0.19 b	0.3 ± 0.02 a	17.5 ± 1.51	0.07 ± 0.01 a	0.6 ± 0.04 a	1.2 ± 0.24 b
H	7.05	11.56	11.56	11.24	3.66	9.97	11.51	10.53
p	0.029	0.0031	0.0031	0.0036	0.1603	0.0063	0.0031	0.0052

Different letters in each column indicate significant (p < 0.05).

Table 4. Mean values (±EE) of soil texture with percentage of silt, clay and sand for each degradation soil conditions (Severe, Moderate, Slight) (n = 30).

Condition	Silt (%)	Clay (%)	Sand (%)
Severe	28.2 ± 1.67 a	5.3 ± 0.37	66.5 ± 1.75 b
Moderate	39.7 ± 0.93 b	5.7 ± 0.98	54.6 ± 1.26 a
Slight	39.3 ± 1.04 b	5.0 ± 0.44	55.7 ± 1.40 a
H	27.02	1.94	25.73
p	<0.0001	0.3797	<0.0001

Different letters in each column indicate significant (p < 0.05).

Table 5. Mean values (±EE) of the most frequent (FA = absolute, and FR = relative in %) morphological features of calafate shrubs (height, maximum and minimum diameters in m) for each degradation soil conditions (Severe, Moderate, Slight) (n = 30).

Condition	Variable	Mean ± EE	FA	FR
Severe	Height	0.78 ± 0.024	13	0.4
	Max. Diameter	1.26 ± 0.033	14	0.5
	Min. Diameter	1.09 ± 0.029	14	0.5
Moderate	Height	0.77 ± 0.020	14	0.5
	Max. Diameter	1.46 ± 0.051	18	0.6
	Min. Diameter	1.11 ± 0.040	16	0.5
Slight	Height	0.91 ± 0.018	9	0.3
	Max. Diameter	1.56 ± 0.051	18	0.6
	Min. Diameter	1.25 ± 0.033	12	0.4

temperature and the highest soil water content in Moderate degradation soil condition content could also be related to the highest tree numbers since canopy and leaf litter regulate soil temperature (Paul et al., 2004), and the canopy shade reduce water evaporation (Lin, 2010), while reducing wind speed (of great importance in Patagonia) (Peri et al., 2016).

The low fruit production per shrub in all the sites also evidence the high degradation level of these soils as the yield decreased more than half
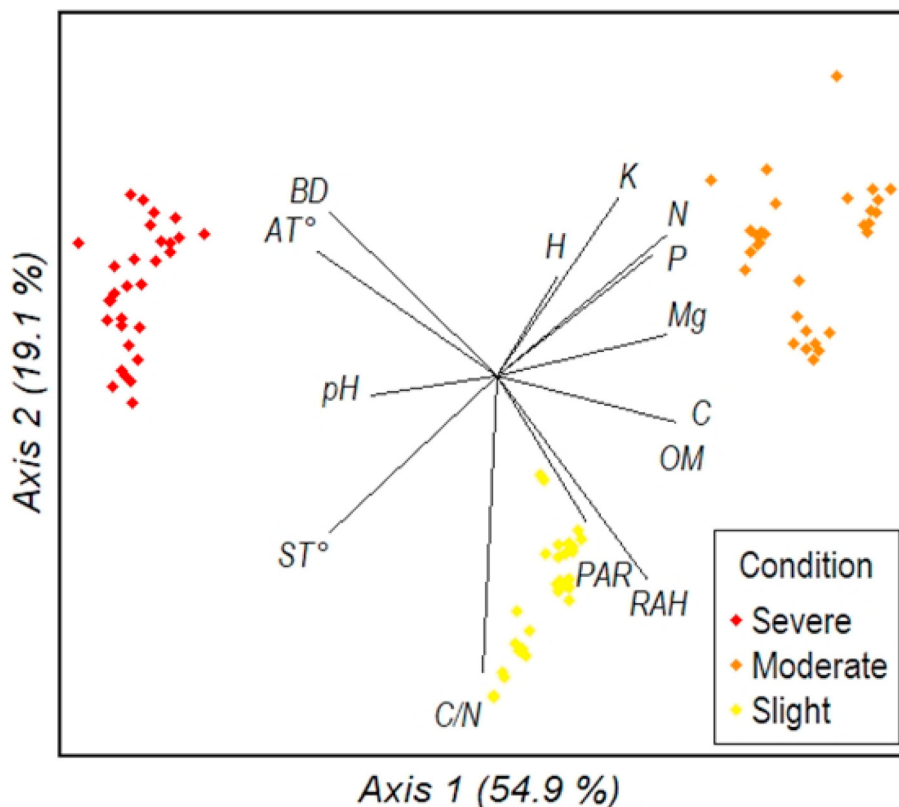

Figure 2. PCA of different climatic and soil variables for each degradation soil conditions (Severe, Moderate, Slight): Soil carbon (C) (%), nitrogen (N) (%), C/N ratio (C/N), magnesium (Mg) (%), phosphorous (P) (%), potassium (K) (%), soil organic material (OM) (%), hydrogen potential (pH), air temperature (T°) (°C), photosynthetically active radiation (PAR) (μmol m² s⁻¹) and soil water content (H°) (%).

Table 6. Mean values (±EE) of the fruit production per shrub volume for each degradation soil conditions (Severe, Moderate, Slight): (F/SV = fruit number (n°.m^{-3}), FW/SV = fruit weight (g.m^{-3})) and per each shrub (F/S = fruit number, FW/S = fruit weight (g) (n = 30) and SF = sound fruits (%) (Severe n = 27, Moderate n = 28, and Slight n = 29).

Condition	F/SV	FW/SV	F/S	FW/S	SF
Severe	22 ± 4.08 a	5.91 ± 1.35 a	15 ± 3.09 a	3.88 ± 0.82 a	72.62 ± 4.79
Moderate	120 ± 36.21 b	38.85 ± 12.20 b	74 ± 16.90 a	24.23 ± 6.07 b	79.75 ± 2.95
Slight	225 ± 49.97 c	76.38 ± 17.98 c	164 ± 30.86 b	56.81 ± 11.43 c	79.69 ± 3.72
H	23.75	27.03	25.73	27.67	0.03
p	<0.0001	<0.0001	<0.0001	<0.0001	0.9849

Different letters in each column indicate significant differences ($p < 0.05$).

Table 7. Mean values of fruit quality variables for each degradation soil condition (Severe, Moderate, Slight): fresh fruit weight (FFW) (g), dry fruit weight (DFW) (g), seed number per fruit (SN), dry seed weight per fruit (DSW) (g), water content per fruit (WC) (%), fruit pulp (FP) (%) and seed (S) (%) (n = 12), and soluble solids (SS) (°Brix) (n = 9).

Condition	FFW	DFW	SN	DSW	WC (%)	FP (%)	S (%)	SS
Severe	0.38 ± 0.0017 a	0.12 ± 0.003 a	6.67 ± 0.283 a	0.05 ± 0.003 a	56.2 ± 0.97 a	31.3 ± 0.53 b	12.5 ± 0.49	22.3 ± 0.36 b
Moderate	0.44 ± 0.0017 a	0.11 ± 0.006 a	6.28 ± 0.300 a	0.05 ± 0.003 a	62.6 ± 0.65 b	26.1 ± 0.38 a	11.3 ± 0.37	20.9 ± 0.51 b
Slight	0.55 ± 0.0017 b	0.17 ± 0.006 b	7.90 ± 0.237 b	0.07 ± 0.003 b	57.8 ± 0.67 a	30.4 ± 0.46 b	11.8 ± 0.27	18.1 ± 0.27 a
H	20.07	21.87	12.07	14.25	20.18	23.72	2.52	12.46
p	<0.0001	<0.0001	0.0023	0.0004	<0.0001	<0.0001	0.2831	0.002

Different letters in each column indicate significant differences ($p < 0.05$).

compared to non-degraded areas (200 g/shrub) (Arena et al., 2018). Soil compaction caused by cattle trampling, generated decreases in calafate fruit production as was observed in other species (Medina, 2016). The most productive site also had the highest relative air humidity and the highest PAR. This resource availability (i.e., light and moisture) are key factors for fruit formation. Relative humidity plays an important role in the pollination process, since it promotes the germination of the pollen grain and the growth of the pollen tube (Faegri and Van Der Pijl, 2013), and therefore in the reproductive efficiency. Light is a particularly key environmental factor for *B. micropylla* that can modulate fruit production through foliar nutrients and pigments (Arena, 2016; Arena et al., 2020). Furthermore, a more humid (i.e., >50% air relative humidity) and warmer environment for this region (over 10 °C) might benefit the reproductive efficiency (Arena et al., 2018) and therefore fruit production.

Regarding fruit quality (key parameters for berries consumption) soluble solids are especially important since they include carbohydrates, organic acids, proteins, lipids and various minerals, being sugar the main component in most fruit (Wills et al., 1981). In our study, the site with the highest soluble solid was the driest soil condition, which had the lowest fruit water content and the highest pulp percentage. This evidence a high concentration of soluble solids due to low water content as was reported in other fruits (Bisson, 2001). Respect individual fruit characteristics, the values were like those previously registered for this shrub species (Arena and Curvetto, 2008; Guastavino et al., 2017; Mc Leod et al., 2017; Pino et al., 2018, 2019). This indicates that even in disturbed sites calafate fruit quality is similar to that of non-degradaded sites. In summary, Severe degradation condition produced fewer fruits but highest pulp proportion per fruit and soluble solids. This fact is striking since Severe sites condition were also the poorest nutrient soils. However, fruit quality could be more related to environmental factors (e.g., water and light availability) rather than soil nutrition. In this sense, Cheng et al. (2014) affirm that the soils with less water and organic matter contributed to the excellent performance of the grape berries.

We determined that fruit production was subject to different soil degradation conditions predefined. However, we considered that the categories do not reflect the extremes of soil degradation condition for these ecosystems, and in reality the Slight and Moderate categories were more similar situations than expected. Future studies should include extreme growing conditions of natural populations of *B. microphylla* (both more degraded and highly conserved) to evaluate the plasticity thresholds of fruits supply.

The results evidence that *B. microphylla* shrubs provide an ecosystem service through their excellent fruits quality in *Nothofagus antarctica* degraded forest. The best productive performance was found in Slight degradation soil condition. At these sites the fruit production could be improved to favor the local development by using this native berry on local food, that are generally related to high-value manufactures (Birgi, 2018).

5. Conclusion

We conclude that *Berberis microphylla* native shrubs should be revalued for their ability to offer an ecosystem service through their excellent fruits quality inclusive in *Nothofagus antarctica* degraded forests. Livestock establishment could diversify their production through this native berries taking advantage of the altered areas occupied by *B. microphylla*. In addition, we recommend avoiding intensive livestock use in burned forest areas since it could lead to irreversible soil erosion. Proper livestock management in these areas could keep the ecosystem provisioning services (fruits, meat, wood) but also the regulating and supporting services overtime offered by native shrubs.

Declarations

Author contribution statement

Gimena Noemí Bustamante: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rosina Soler: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ana Paula Blazina: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Miriam Elisabet Arena: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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