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Research paper

Biomass valorization in the management of woody plant invaders: The case of *Pittosporum undulatum* in the Azores

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ABSTRACT

As one cause for biodiversity loss, invasive alien species are a worldwide threat. However, exotic woodland can also have an enormous biomass potential. The goal of this study was to evaluate the available aboveground biomass (*AGB*, including trunk, branches and foliage) of the widespread woody plant invader *Pittosporum undulatum* in the exotic woodland in São Miguel, Terceira and Graciosa islands (Azores archipelago), in order to assess its potential for energetic valorization. We used different modeling approaches in combination with forest inventory data to estimate total *AGB*. We sampled 127 stands dominated by *P. undulatum*, estimated stand density, measured diameter at breast height, basal area, tree height, and number of branches at breast height in a total of 5872 trees, and determined the *AGB* of 674 trees. Allometric equations were used to estimate *AGB* from dendrometric traits ($R^2 = 0.88$). Although it was possible to predict stand biomass based on stand density and on dendrometric traits, there was no clear relationship between *AGB* and topographic and climatic variables. Using average estimates of *AGB*, the areas classified as dominated by *P. undulatum* in the forest inventory, and a rotation period of 26 years, we calculated a total annual available *AGB* of 1570, 2594 and 11903 Mg. year^{-1} for Graciosa, Terceira and São Miguel islands, respectively. The employed methods and the results obtained in this work provide the means for a more accurate evaluation of the woody biomass resources, opening new perspectives for the management of woody plant invaders.

1. Introduction

Invasive alien species (IAS) pose a continuous threat to ecosystems worldwide, especially as a cause for biodiversity loss, and through the possibility of modifying key ecological processes [1–4]. Monitoring invasive species, preventing their further spread, and diminishing or even eradicating populations of IAS, is vital, particularly in those cases where ecosystem services are negatively affected [5,6].

Forests and woodlands provide a wide range of services, such as wood for fuel, which in temperate forests is now viewed as a major source of energy [7]. However, non-indigenous trees now feature prominently on the lists of invasive alien plants in many parts of the world. In many areas, non-indigenous woody species are now among the most conspicuous and damaging, and many alien trees and shrubs are blacklisted or controlled in Europe and elsewhere, such as *Acer negundo*, *Acacia* spp., *Ailanthus altissima*, *Pinus* spp., *Prunus serotina*, *Quercus rubra* and *Robinia pseudoacacia* [4]. Hence, the Council of Europe has promoted the preparation of a *Code of Conduct on Planted Forest and Invasive Alien Trees* [8]. That code provides guidelines focusing on key invasion pathways and in the implementation of prevention and mitigation actions

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[9]. Despite their potentially harmful effect, IAS have been used as woody crops in forestry, being suitable as bioenergy sources. Due to their relatively short rotation cycles [10], IAS have been used in silvicultural systems based upon short clear-felling cycles, generally between one and 15 years, employing intensive cultural techniques such as fertilization, irrigation and weed control, and utilizing genetically superior planting material [11]. Additionally, invasive tree species also grow faster and accumulate more biomass than native plants in the same ecosystem, and have an enormous biomass potential that can be harvested while taking control measures [12,13]. The use of IAS biomass has been based on two different approaches: (i) crops grown specifically for bioenergy production [14,15]; and (ii) the valorization of the biomass already in place [16–18]. The most common woody species used in short rotation cycles belong to the genera *Populus*, *Eucalyptus*, *Salix*, *Paulownia*, *Robinia*, *Platanus* and *Acer* [19]. The interest in the use of *Eucalyptus* derives from its higher energetic potential compared to other fast growing species, such as *Populus* and *Paulownia* [10]. Within *Eucalyptus*, the energy potential of residual biomass has been found to be higher for *E. nitens* than for *E. globulus* [10]. Also, the aboveground biomass (*AGB*) of *Prunus serotina*, *Robinia pseudoacacia* and *Ailanthus altissima* has been used for fuel production [12,20].

AGB is a key variable in forest monitoring programs, in the management of forest resources at local level, and in forest planning at regional and international levels. Estimates of *AGB* are necessary for assessing the availability of wood fuel and timber, and for monitoring forest carbon stocks [21]. *AGB* is commonly divided into main stem or trunk, branch wood and foliage [22], and it is estimated through the use of allometric equations that relate it with easily measurable attributes such as diameter at breast height (*D*), total tree height (*H*), number of branches (*NB*) and basal area (*BA*) [23].

In the Azores archipelago, *Pittosporum undulatum* Vent. (Pittosporaceae) is the most widespread woody plant invader, where it is considered as one of the priority species for control actions, but also as a species with a high potential for energetic valorization, due to the low ash content and relatively high calorific value of its biomass [16]. Several studies linked environmental factors and the potential distribution of *P. undulatum* [24–28] and Gil et al. [29] mapped invasive woody plant distribution in Azores protected areas through remote sensing. However, there is no information on the spatial distribution of *P. undulatum AGB*, and the estimates of its biomass availability have been based on a very general approach [16] or have focused on very precise locations [30]. One way to specifically describe biomass variation along an environmental gradient, and to detect fine scale relationships of potential factors influencing its distribution, is through the mapping of *AGB* distribution with spatially-explicit information for each recorded individual or stand [31]. Therefore, the energetic valorization of *P. undulatum* biomass will depend on more accurate estimates of *AGB*, particularly if private and public investment in the development of industrial facilities will depend on a sustainable supply of woody biomass [23], and if an accurate evaluation of the ecosystem services provided by the Azorean exotic woodland dominated by *P. undulatum* is required.

In this research we did not focus on the introduction of IAS to produce biomass, but on the possibility of including the energetic valorization of woody biomass as another tool to help in the sustainable management of the widespread invader *P. undulatum*. We aim to provide managers and investors with sound information on *P. undulatum AGB*, opening the possibility for its use, if considered as environmentally and economically justified. Therefore, the goal of this study was to evaluate the annual production of *P. undulatum AGB*, within the exotic woodland present in São Miguel, Terceira and Graciosa islands, where private projects and industrial facilities and for the use of woody biomass are planned or already in place [32,33]. We focused on exotic woodland dominated by *P. undulatum*, since those areas where this species is not dominant will most likely have other management goals, such as conservation areas (i.e., protected areas that are invaded and should be recovered) or production forest (e.g., *Cryptomeria japonica* forest for certified timber production).

Our specific objectives were: (i) to estimate *AGB* of *P. undulatum* trees using previously validated allometric equations [23]; (ii) to determine *P. undulatum* stand density using previously tested methods [34]; (iii) to evaluate the possibility of modeling *AGB* based on ecogeographical variables, to be able to predict *AGB* in the large extensions occupied by the invader, if possible, without the need to use intensive field work; and (iv) to refine the *AGB* estimation of *P. undulatum* for the three studied islands.

This evaluation will not only be useful for management purposes in the Azores but it could also be used as a model for similar evaluations targeting other species or regions.

2. Material and methods

2.1. Study area

The Azores archipelago is located between North America and Europe, about 1500 km west of mainland Portugal, between 36°55′N and 39°42′N and 25°00′W and 31°30′W (Fig. 1). The archipelago consists of nine inhabited islands of volcanic origin with a total land surface of 2323 km^2. The climate is temperate oceanic with a mean annual temperature of 17 °C at sea level, relative humidity is high and rainfall ranges from 1500 to more than 3000 mm per year, increasing with altitude and from east to west [35]. This study took place in three islands: São Miguel with a surface area of 745 km^2 and the highest elevation at 1105 m above sea level [35]; Terceira with a surface area of 400 km^2 and the highest elevation at 1021 m [36]; and Graciosa with a surface area 62 km^2 and the highest elevation at 402 m [37]. We selected those islands because private companies are developing projects therein in order to use woody biomass for pellet or electricity production [32,33]. Azorean production forest presently relies almost entirely on *Cryptomeria japonica*, with a relatively long production cycle (30 years) [16], and wood residues from this species are already being used for woody pellet production. In the Azores, natural forests most probably dominated the landscape prior to human settlement [38,39]. However, natural forests were largely cleared and replaced by production forest, exotic woodland or pastureland. The natural vegetation presently occupies 13% of the territory and, includes diverse communities, namely coastal vegetation, inland wetlands, meadows, and several types of native forest and scrubland [38–40].

2.2. Target species

Pittosporum undulatum is a tree or shrub native to Australia that was introduced in the Azores during the 19th century [41], and is considered as an invasive species in several regions, such as Hawaii, Jamaica, South Africa, and other Pacific and Atlantic islands [42]. This invader has the ability to overgrow the native vegetation by shading the indigenous species and forming pure stands, particularly in sheltered locations. This introduction altered the natural transition between the native plant communities, which were found between 300 and 600 m of altitude [43]. According to a random survey by Lourenço et al. [16], *P. undulatum* was found in a wide range of habitats in pure or mixed stands, and was often found in native scrubland (62%), mixed woodland (39%) and hedgerows (25%). Its altitudinal range extends from sea level up to about 800 m a.s.l., with the highest frequency between 100 and 400 m [16]. It is associated with a wide variety of other introduced woody species such as *Acacia melanoxylon*, *Eucalyptus globulus* and *Pinus pinaster*, and more rarely with *Persea indica* [16].

2.3. Forest inventory

Pittosporum undulatum invades about 23891 ha (49%) from a total of 49070 ha occupied by forest in the Azores archipelago, where it forms