It loves me, it loves me not! Unravelling the spatial coincidence between alien invasive species and ecosystem services

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Resumo

A perda de biodiversidade está a aumentar globalmente a uma taxa sem precedentes, onde fatores diretamente relacionados com o ser humano, como a introdução de espécies exóticas invasoras, atuam como fortes impulsionadores dessa perda. As plantas exóticas invasoras impactam os ecossistemas de variadas formas dependendo da espécie que invade, do tempo de residência da espécie na região, da área de distribuição, entre outros. Estas espécies têm variados impactos não só na biodiversidade, mas também nos serviços dos ecossistemas de aprovisionamento, regulação e culturais. Estes últimos, representam as oportunidades de interação (intelectual ou física) do ser humano com a natureza, incluindo por exemplo atividade de recreação e visitação. Alguns estudos têm previsto que as alterações climáticas e mudanças no uso da terra podem atuar sinergicamente no favorecimento da expansão de plantas exóticas invasoras para novos ecossistemas. Os modelos de distribuição de espécies são amplamente utilizados para antecipar novas introduções e prever distribuições atuais e futuras de espécies, incluindo de plantas exóticas invasoras. Acoplando os resultados dos modelos com cenários futuros de alterações climáticas, estes podem contribuir para medidas de gestão e conservação mais eficientes. De igual forma, constituem uma ferramenta de apoio para avaliar e antecipar possíveis conflitos com os mais variados valores naturais, inclusive aqueles derivados de serviços culturais de visitação, podendo apresentar-se como medidas de apoio a ações de conservação.

O presente estudo teve como objetivo identificar possíveis conflitos espaciais entre a distribuição de plantas exóticas invasoras e as áreas de provisão de serviços dos ecossistemas culturais, expressos pelo interesse de visitação da paisagem. Para isso, analisou-se o caso da distribuição de três espécies de *Acacia* no Norte de Portugal, pretendo responder a três perguntas principais: (i) as áreas de maior potencial de invasão são coincidentes com as áreas de maior interesse de visitação? (ii) essa coincidência espacial mantém-se perante cenários de alteração climática? (iii) quais as principais implicações de gestão? Para tal, foram usados dados de fotografias extraídas da plataforma de rede social, Flickr, para mapear o interesse de visitação, bem como projeções da distribuição potencial das três espécies produzidas segundo uma abordagem de modelagem preditiva combinada proveniente de um estudo prévio. Os resultados obtidos permitiram identificar hotspots de visitação coincidentes com áreas de presença das espécies exóticas invasoras estudadas, principalmente no litoral e centro do Norte de Portugal. Os resultados revelaram também que as áreas de coincidência espacial entre o interesse de visitação e a distribuição das três espécies de *Acacia* poderão alterar-se no futuro devido a mudanças das condições ambientais. As implicações resultantes podem contribuir para implementar medidas de gestão mais eficientes de diferentes paisagens no Norte de Portugal. A abordagem utilizada realça a importância de mapear serviços dos ecossistemas culturais para entender como as sociedades interagem com eventos de mudança ambiental, como espécies de plantas exóticas invasoras, atualmente e no futuro.

Palavras-chave: alterações climáticas, coincidência espacial, interesse de visitação, modelos de distribuição de espécies, plantas exóticas invasoras, redes sociais

Abstract

Biodiversity loss is increasing globally at an unprecedented rate, where factors directly related to humans, such as the introduction of invasive alien species, act as strong drivers of this loss. Invasive alien plants impact ecosystems in different ways depending on the species that invade, the time of residence of the species in the region, and the area of distribution, among others. These species have varied impacts not only on biodiversity but also on provisioning, regulatory and cultural ecosystem services. The latter represent opportunities for human interaction (intellectual or physical) with nature, including, for example, recreation and visitation activities. Some studies have predicted that climate change and changes in land use may act synergistically in favoring the expansion of invasive alien plants into new ecosystems. Species distribution models are widely used to anticipate new introductions and predict current and future distributions of species, including invasive plants. By coupling the model results with future climate change scenarios, these can contribute to more efficient management and conservation measures. Likewise, they constitute a support tool to assess and anticipate possible conflicts with the most varied natural values, including those derived from cultural visitation services, and may present themselves as support measures for conservation actions.

The present study aimed to identify possible spatial conflicts between the distribution of invasive alien plants and the areas of provision of cultural ecosystem services, expressed by the interest in landscape visitation. For this, the case of the distribution of three *Acacia* species in the North of Portugal was analyzed, aiming to answer three main questions: (i) do the areas with the highest potential for invasion coincide with the areas of highest interest for visitation? (ii) does this spatial coincidence remain in the face of climate change scenarios? (iii) what are the main management implications? To this end, data from photographs extracted from the social networking platform, Flickr, were used to map visitation interest, as well as projections of the potential distribution of the three species produced according to a combined predictive modelling approach from a previous study. The results obtained allowed us to identify visitation hotspots that coincide with areas of presence of the invasive alien species studied, mainly in the coast and center of the North of Portugal. The results also revealed that the areas of spatial coincidence between the visitation interest and the distribution of the three *Acacia* species may change in the future due to changes in environmental conditions. The resulting implications may contribute to implementing more efficient management measures for different landscapes in the North of Portugal. The approach used highlights the importance of mapping cultural ecosystem services to understand how societies interact with environmental change events, such as invasive alien plant species, now and in the future.

Keywords: climate change, invasive alien plants, social networks, spatial coincidence, species distribution models, visitation interest

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List of abbreviations

CBD Convention on Biological Diversity

EU European Union

GIS Geographic Information System

ICNF Instituto da Conservação da Natureza e das Florestas

IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Km Kilometre

MEA Millennium Ecosystem Assessment

UTM Universal Transverse Mercator

WWF World Wildlife Fund

1. Introduction

1.1. Invasive alien plant species

Global biodiversity is facing an increasing decline in recent decades (IPBES, 2019; WWF, 2020), with one of the main drivers being the introduction of invasive alien species (IPBES, 2019; Seebens *et al*., 2017; Stoett *et al*., 2019). The creation of new trade routes and increased human movement has facilitated the intentional or accidental introduction of species into new areas where they did not previously exist (Hulme, 2009; Humair *et al*., 2015; Meyerson and Mooney, 2007). Additionally, with the development of e-commerce, it has become easier and faster than ever to discover, buy and transport products (Humair *et al*., 2015; Rodrigue *et al*., 2016; Wu *et al*., 2017). This is particularly important in the introduction of plant species, as transport rates have increased exponentially since the 19th century, remaining high to the present day (Hulme, 2015; Seebens, *et al*., 2015).

Alien plant species have been introduced by humans for a variety of reasons, from wood production (e.g., *Pinus* spp., *Eucalyptus* spp.), restoration of forests and landscapes, ornamental use (e.g., *Acacia* spp.) or soil erosion control (e.g., *Acacia* spp., *Pinus* spp.) (Brundu & Richardson, 2016; Carruthers *et al*., 2011; Hulme *et al*., 2018; Kull *et al*., 2011; Lelmini & Sankaran, 2021). However, many of these alien species have become invasive, i.e., widely spread, auto-sufficient, and with severe social-ecological impact at introduction sites (Richardson *et al*., 2000; Richardson & Rejmánek, 2011). Invasive plant species are amongst the most problematic invasive alien species in various regions (Lowe *et al*., 2000; Nentwig *et al*., 2018; Richardson & Rejmánek, 2011). Although invasive alien plants are globally distributed, more developed regions, such as Europe, tend to concentrate a greater number of invasive alien plants, due to the history of importing these species for horticulture and ornamentation (Tuberlin *et al*., 2016). At the same time, in an increasingly globalized and connected world, the introduction of potentially invasive alien species is expected to continue to increase (Seebens *et al*., 2017).

Some studies have shown that changes in environmental conditions (e.g., temperature and precipitation), induced by current climate change (IPBES, 2019), may favor not only the proliferation of invasive alien plants, but also their expansion to regions where they were previously unable to settle down (Hulme *et al*., 2017; Kleinbauer *et al*., 2010; Lamsal *et al*., 2018; Poland *et al*., 2021; Walther *et al*., 2009). In addition, climate change may change the direction and intensity of impacts caused by invasive alien plants (Hulme *et al*., 2017), threatening further ecosystem functioning and human well-being (IPBES, 2019; Li *et al*., 2018; Pejchar & Mooney, 2009; Stoett *et al*., 2019; WWF, 2020).

1.1.1. From alien to invasive

The process of biological invasion occurs when a species is displaced outside its native range through human-mediated processes, spreading and causing impacts in the new area (Richardson *et al*., 2000; Richardson & Rejmánek, 2011). Such dispersion may be due to human-mediated drivers (e.g., transportation) and by natural ones (e.g., water, wind), and occur at different time scales, from years to centuries (Dogra *et al*., 2010). According to Blackburn *et al*. (2011), based on Williamson (1996) and Richardson *et al*. (2000), the invasion process usually follows four phases, namely, transport, introduction, establishment, and dispersion (Figure 1). For each of the stages, there are sequential geographic, survival, reproduction, and dispersal barriers that species must overcome to reach, survive, and disperse in a new ecosystem until becoming invasive. Depending on the stage of invasion, species are classified differently, and different management measures can be considered (Blackburn *et al*., 2011) (Figure 1).

The geographic barrier occurs when the species are transported by humans to new places (Seebens *et al*., 2016, 2017). After being introduced outside their native range, these species then become alien species (also referred to as “exotic” or “non-native”; Richardson *et al*., 2000). Most alien species have a limited distribution in the receiving ecosystems, coexisting in equilibrium with native plant species (Blackburn *et al*., 2011; Marchante *et al*., 2014). Alien species can be classified as either casual or naturalized (Figure 1), depending on whether they require human intervention and repeated introductions to form self-maintaining populations or not, respectively (Blackburn *et al*., 2011; Marchante *et al*., 2014). However, a small part of alien plants is considered invasive when they produce abundant and independent reproductive populations, both spatially and temporally, and have an impact on local ecosystems and species (IPBES, 2019; Richardson & Rejmánek, 2011).

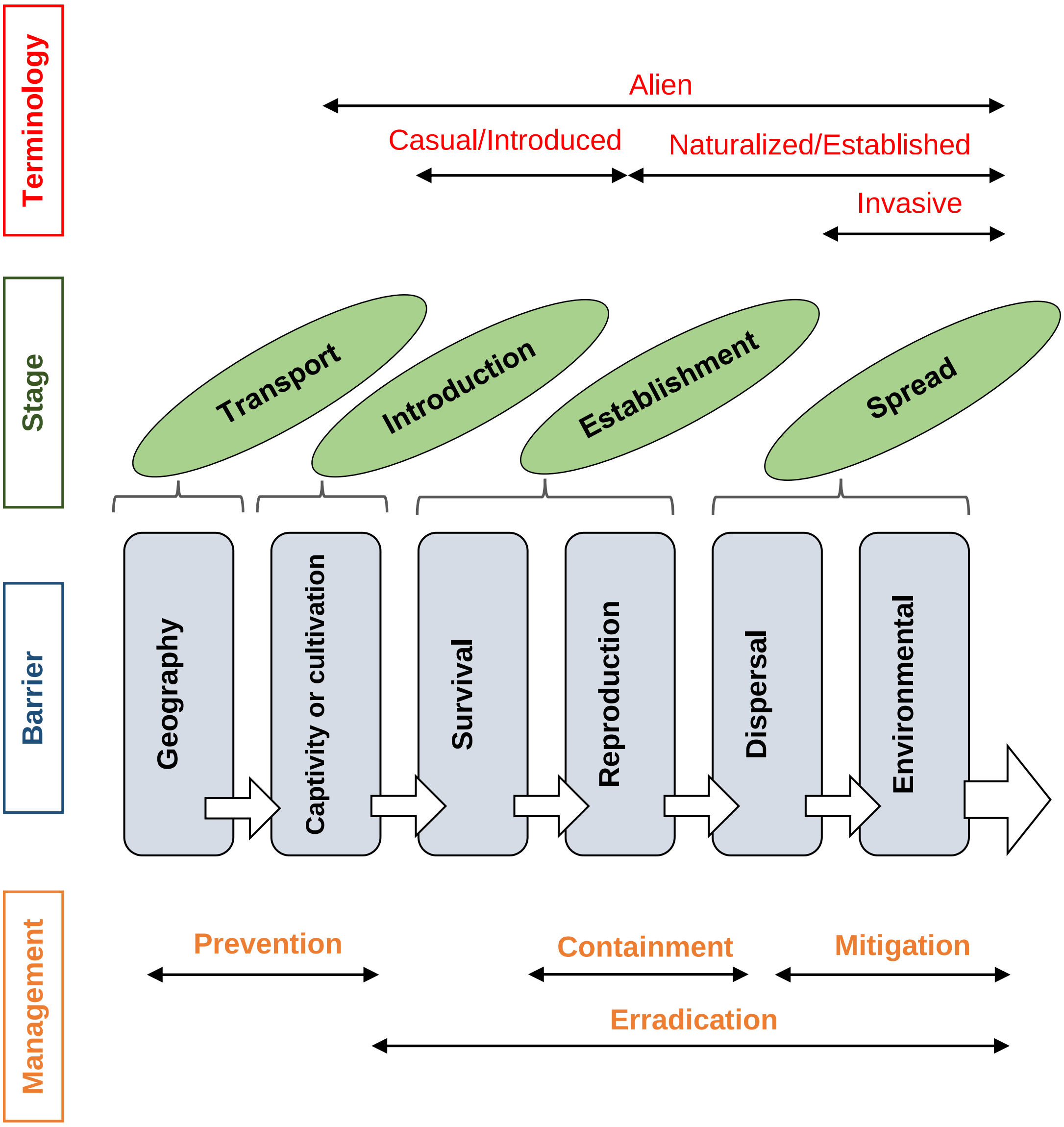

Figure 1 | Framework proposed by Blackburn *et al*. (2011) to illustrate the invasion process. The process is divided into four phases, where in each of them there are biotic and abiotic barriers that a species or a population must overcome to move on to the next phase until it becomes invasive. The framework also indicates the terminology given to a species depending on the stage of invasion, as well as the desirable management options. White arrows indicate the direction of species or populations throughout the four phases of the invasion continuum. Adapted from Blackburn *et al*. (2011).

The success of the invasion process is intrinsically related to invasiveness, that is, the attributes of the plant species that give them the ability to invade (e.g., ability to fertilize and disperse seeds, number of seeds, time and duration of flowering, phenotypic plasticity). The invasion success also depends on invasibility, which is related to the characteristics of the receiving ecosystem and which determine its vulnerability to invasion (e.g., degraded/fragmented landscapes; Gaertner *et al*., 2014; Pyšek *et al*., 2012; Richardson & Pysek 2006; Vicente *et al*., 2010). The synergic interactions between environmental factors, such as climate (e.g., precipitation and temperature) and landscape composition and structure (e.g., land use patterns, disturbance regimes), play a strong role on the expression of invasiveness and invasibility and may determine whether a casual or naturalized alien plant becomes invasive or not, as well as the spatial distribution of invasive alien species (Marchante *et al*., 2014; Poland *et al*., 2021; Vicente *et al*., 2010, 2014).

In this sense, environmental drivers, such as climate change, can create suitable conditions for an alien plant to become invasive, due to the increase in the probabilities of survival, growth, and persistence of its populations in the receiving ecosystem (Chown *et al*., 2012; Hulme *et al*., 2017; Loomans *et al*., 2013). Likewise, future changes in such environmental drivers may promote the spread of invasive alien plants in new habitats where they were previously unable to establish themselves (Hellmann *et al*., 2008; Kleinbauer *et al*., 2010; Lamsal *et al*., 2018; Poland *et al*., 2021; Walther *et al*., 2009). Also, disturbances caused by humans, such as the degree of intensity of land use or the existence of dispersal paths such as roads, and other infrastructure, can facilitate the spread of invasive alien plant species (Kueffer, 2017; Marchante *et al*., 2014; Vicente *et al*., 2010, 2014).

1.1.2. Impacts and management

Invasive alien plants can alter biogeochemical cycles (e.g., water, energy, and nutrients) (Marchante *et al*., 2008, 2014), biotic dynamics, and interactions in receiving ecosystems (Gaertner *et al*., 2014; Ricciardi *et al*., 2017; Vilà *et al*., 2011; Zhang *et al*., 2019), as well as fire regimes (Marchante *et al*., 2014; Pyšek *et al*., 2012; Souza-Alonso *et al*., 2017). One of the best documented and perceived impacts of invasive alien plants is the fact that they replace native flora through competition for resources, decreasing the richness of local species and contributing to the homogenization of landscapes (Lelmini & Sankaran, 2021; Marchante *et al*., 2014; Shackleton *et al*., 2017). Furthermore, socio-economic activities can be affected, as invasive alien plants can invade infrastructure (e.g., roads, railways) and production areas, resulting in high costs associated with the loss of assets and the removal and control of invasive plants (Kettunen *et al*, 2008; Marchante *et al*., 2014; Rai & Shing, 2020). Public health can also be harmed due to disease (e.g., allergies), pest dispersal, or change in environmental quality caused by invasive plants (Jones & McDermott, 2018; Marchante *et al*., 2014; Rai & Shing, 2020; Stone *et al*., 2018).

Nonetheless, invasive alien plants can simultaneously be used by people due to the goods and key resources they provide in many regions (Castro-Díez *et al*., 2019; Dickie *et al*. al., 2014; Shackleton *et al*., 2019a; Vaz *et al*., 2017a, 2019). For example, many local communities depend on the production, use and/or sale of wood provided by some invasive alien plants (most commonly from the genera *Pinus, Eucalyptus* and *Acacia*) as a source of subsistence and income (Dickie *et al*. al., 2014; Kull *et al*., 2011; Shackleton *et al*., 2019a). Other invasive plants are considered a food source or used for ornamentation, natural medicines, or cosmetics (Dickie *et al*., 2014; Scott, 2010; Shackleton *et al*., 2011, 2014, 2015).

The impacts caused by invasive alien plant species are multidirectional, depending on the geographic of the species distribution (invasibility), the species itself (invasibility traits), and the time of residence of the species in the region (Castro *et al*., 2005; Marchante *et al*., 2008). For this reason, the management of biological invasions is a complex process, nonetheless crucial for the conservation of biodiversity and ecosystems invaded (Brundu & Richardson, 2016).

The management of impacts caused by invasive alien plants encompasses three main types of response depending on the stage of the invasion process (Figure 1): prevention, early detection, and control (Blackburn *et al*., 2011; Marchante *et al*., 2014; Meyerson & Mooney, 2007). Prevention involves the implementation of measures that can anticipate and avoid new introductions of potentially invasive exotic plants, such as the use of species distribution models (Elith & Leathwick 2009; Poland *et al*., 2021), and the application of legislation that restricts and controls the use of already introduced species (Marchante *et al*., 2014). When prevention fails, management subsequently falls into monitoring and early detection options to allow their effective removal through eradication (Blackburn *et al*., 2011; Marchante *et al*., 2011, 2014). However, when the naturalization of alien plant species occurs and, subsequently, a rapid and indiscriminate increase in their areas of dissipation, invasion control options can be set, through the containment of the invaded area, to reduce the spread and mitigate impacts (Marchante *et al*., 2014). Given the difficulty and costs associated with eradicating and controlling established invasive plant populations, as well as the irreversible losses they can cause (Marchante *et al*., 2014; Rai & Shing, 2020; Rejmánek *et al*., 2013), prevention of alien plants introductions is recognized as the most cost-efficient option (Genovesi, 2005; Lelmini & Sankaran, 2021; Poland *et al*., 2021).

1.1.3. Invasion management support through modelling

To assist in the prevention, early-detection and monitoring of invasive species, species distribution modelling has become a popular approach. Species distribution modelling is widely used to investigate spatial and temporal invasion patterns of alien plants in ecosystems (Barbet-Massin *et al*., 2018; César de Sá *et al*., 2019; Dinis *et al*., 2020; Poland *et al*., 2021; Vicente *et al*., 2013, 2016, 2019). Such models relate geographic occurrence data (presence/absence or abundance) of species with environmental variables that act at different spatial scales to predict where and why the species may occur in a given place (e.g., land use, climate; Elith & Leathwick, 2009; Guisan & Thuiller, 2005; Pearson *et al*., 2004; Vicente *et al*., 2010, 2011, 2014). Thus, these models can be applied to predict potential introductions of invasive alien plants into ecosystems prior to invasion (Elith & Leathwick 2009; Martins *et al*., 2016; Poland *et al*., 2021); to anticipate the potential invasion areas in a given ecosystem (Fernandes *et al*., 2014; Poland *et al*., 2021; Vicente *et al*., 2010, 2011, 2019); or even to assess the potential impacts of invasive alien plants and the effectiveness of applied control measures (Dinis *et al*., 2020; Poland *et al*., 2021; Santos *et al*., 2015; Thompson *et al*., 2011). In a nutshell species distribution models represent a useful tool in managing the different stages of a biological invasion process, contributing not only to the identification of potential invasion threats but also for improving the monitoring and mitigation of existing invasions (Carvalho *et al*., 2011; Crall *et al*., 2013; Honrado *et al*., 2016).

Additionally, species distribution modelling has been increasingly applied to project potential areas of distribution of invasive alien plants under future climate change conditions (Lamsal *et al*., 2018; Poland *et al*., 2021; Thapa *et al*., 2018; Vicente *et al*., 2013, 2016). As the processes of invasion by alien plants can interact synergically with climate change and the impacts on the receiving ecosystems can be higher than those initially expected (Hulme *et al*., 2017), the combination of species distribution models with future climatic scenarios (Nakicenovic & Swart, 2000) allows to identify and prioritize invasive alien species and habitats at risk of invasion (Lamsal *et al*., 2018; Poland *et al*., 2021; Shrestha *et al*., 2019; Thapa *et al*., 2018; Vicente *et al*., 2013, 2016). Therefore, species distribution models are useful tools to prioritize the allocation of management resources but also to implement more efficient, informed, and adaptive management measures.

1.2. Cultural ecosystem services

Invasive alien plants significantly impact the receiving ecosystems, being responsible for altering ecosystem services at various levels (Castro-Díez *et al*., 2019; Milanović *et al*., 2020; Vaz *et al*., 2017a). These ecosystem services represent the material and immaterial contributions that nature provide to people which are essential for human well-being (Díaz *et al*., 2015; MEA, 2005; Singh, 2002). These contributions include regulation services (e.g., pollination, biological control, carbon sequestration) and provisioning services (e.g., food production, energy, fiber), but also cultural services.

Cultural ecosystem services comprise the non-material contributions that people derive from ecosystems through physical (e.g., recreational experiences and ecotourism) and/or spiritual (e.g., aesthetics and heritage or inspirational values) interactions (Chan *et al*., 2011; Fish *et al*., 2016; MEA, 2005). Increasingly, this contact with nature resulting from cultural services has been associated with physical and psychological well-being (Bratman *et al*., 2012, 2015; Hansmann *et al*., 2007; Kotera *et al*., 2022; Nesbitt *et al*., 2017), leading to the term *Shinrin-yoku* which means "forest bathing", since it can promote the reduction of physiological signs of stress and fatigue, among others (Kotera *et al*., 2022; Lee *et al*., 2014 ; Park *et al*., 2008, 2010). Thus, cultural services represent an opportunity to address the intrinsic interactions between people and their surrounding environment (Díaz *et al*., 2015; Martín-Lopéz *et al*., 2012; Oteros-Rozas *et al*. al., 2014). For instance, cultural ecosystem services can trigger a “sense of place”, that is, a person’s or community’s sense of security and belonging to a particular place, as well as a connection with nature (Cuerrier *et al*., 2015; Poe *et al*., 2016). Likewise, cultural services drive people’s interest to visit certain natural areas, or engage in specific recreational or leisure activities (Bachi *et al*., 2020; Mouttaki *et al*., 2021; Ram & Smith, 2022; Vaz *et al*., 2020; Zoderer *et al*., 2016).

1.2.1. Visitation interest and cultural services

There is an increasing displacement of people worldwide in the pursuit of visitation areas that offer cultural services. Nature-based visitation has been recognized as one of the main activities that most contribute to the socioeconomic development of many countries (Santarém *et al*., 2020; Wood *et al*., 2018) and visitation interest rates are expected to increase in the future (Balmford *et al*., 2009). Visitation interest is motivated by nature-based activities associated to cultural services, such as hiking, wildlife watching, and extreme sports, among others (Brambilla & Rochi, 2020). Generally, these practices are also associated with natural and aesthetic values, as the public looks for places for recreation and visitation based on the attractiveness of the landscape and the biodiversity they offer (Hausmann *et al*., 2016; Vaz *et al*., 2020; Zoderer *et al*., 2016).

Furthermore, outdoor recreation and ecotourism are motivated by cultural and natural values that typically reflect people's preferences and what is important to them (Chan *et al*., 2012). Thus, understanding which areas are most valued by society based on visitor interest becomes increasingly important for a more sustainable management of ecosystems and land use (Cabana *et al*., 2020; Plieninger *et al*., 2013, 2015). To this end, mapping cultural services through the assessment of nature-based visitation patterns represents a promising approach (Martín-Lopez *et al*., 2012; Mouttaki *et al*. 2021; Smart *et al*., 2021; Tieskens *et al*., 2017).

Landscape attributes such as topography, vegetation cover, presence or absence of water bodies, accessibility or offer of historical heritage contribute to the visitation of certain places, to the detriment of others (Brown & Brabyn, 2012; Plieninger *et al*., 2013; Vallecillo *et al*., 2019; Vaz *et al*., 2020). For example, Clarke *et al*. (2021) and Mouttaki *et al*. (2021) demonstrated that landscape features and the variety of recreational activities present in coastal areas were associated with greater visitation by people. On the other hand, rural and more inland areas, where access is scarce, tend to have a lower capacity to promote cultural services of interest to visitors (Bachi *et al*., 2020).

Different landscape mosaics represent different cultural contributions of nature to people (Tieskensa *et al*., 2018; Vaz *et al*., 2020), and hence visitation interest to certain areas. For instance, Vaz *et al*. (2020) investigated the potential for visitation interest in two contrasting protected areas, with mountain versus coastal landscapes, showing different geographic patterns in the interest pursuit for rural tourism, recreational activities and sports (e.g., ski) compared to wildlife observation and cultural heritage. Other authors have also shown distinct visitation interests over landscapes and areas, depending on the natural environmental, such as land use type (Balmford *et al*., 2015; Clemente *et al*., 2019; Hausmann *et al*., 2016, 2017; Pastur *et al*., 2016).

There is a general agreement that land use influences visitation interest, depending on people's preferences (Martín-Lopez *et al*., 2012; Plieninger *et al*., 2015). Typically, more diverse landscapes mosaics, with forests, traditional agroforestry systems, rural or urban areas, and wine-growing areas, among others, provide opportunities for more cultural services and hence drive people’s visitation preferences

(López-Santiago *et al*., 2014; Plieninger & Bieling, 2012; Tieskens *et al*., 2017). The ability of different landscapes to promote cultural services that meet the preferences of different groups of visitors results in heterogeneous spatial patterns of nature-based visitation interest (Bachi *et al*., 2020; Pastur *et al*., 2016; Plieninger *et al*., 2013), where higher visitation rates (cultural hotspots) and areas with lower tourist potential may emerge (Bachi *et al*., 2020; Bagstad *et al*., 2017; Karimi *et al*., 2020; Ridding, *et al*., 2018; Yoshimura & Hiura, 2017).

1.2.2. Accessing visitation patterns

There are many ways to access visitation patterns, from questionnaire-based approaches to visitor surveys (Di Minin *et al*., 2015; Hausmann *et al*., 2017; Tenkanen *et al*., 2017). Still, many of these conventional approaches are difficult to implement, being too costly for wide areas and to reach a continuous monitoring (Di Minin *et al*., 2015). In a highly technological era, the use of information retrieved from social media networks (e.g., Instagram, Twitter, Panoramio, Flickr) has become a promising approach to access visitors' patterns in nature (Di Minin *et al*., 2015; Richards & Friess, 2015; Tenkanen *et al*., 2017). Such is mainly because people increasingly use the internet to share their experiences and activities in nature (Di Minin *et al*., 2015; Ruths & Pfeffer, 2014; Toivonen *et al*., 2019), offering large volumes of data (e.g., photographs, videos, tags, or texts; Kitchin *et al*., 2014) to help comprehending visitation interests over cultural services' opportunities in near real-time.

Particularly when social media data is georeferenced it becomes useful to investigate tourist movements in different environments (Heikinheimo *et al*., 2017), to estimate the number of visitors in protected areas (Karimi *et al*., 2020; Sonter *et al*., 2016; Tenkanen *et al*., 2017; Toivonen *et al*., 2019; Wood *et al*., 2013), to investigate visitation patterns taking into account landscape context (Cardoso *et al*., 2022; Figueroa-Alfaro & Tang, 2017; Moreno-Llorca *et al*., 2020; Mouttaki *et al*., 2021; Vaz *et al*., 2020) or the role of visitation drivers, such as invasive alien species (Daume, 2016; Di Minin *et al*., 2015; Edwards *et al*., 2021; Vaz *et al*. 2019a).

1.3. Invasive alien plants as drivers of visitation interest

How the presence of invasive alien plants affects people's preferences for cultural services, and particularly visitation interests, is poorly understood (Kueffer & Kull, 2017; Vaz *et al*., 2018). Some studies have sought to investigate the relationship between the presence of invasive alien plants and the interest in nature-based visitation (Carruthers *et al*., 2011; Castro-Díez *et al*., 2019; Dickie *et al*., 2014; Vaz *et al*., 2017a, 2018, 2019). For instance, Vaz *et al*. (2018) showed evidence that official tourism entities tend to highlight invasive alien plants in their advertisements to attract visitors to tourist destinations in the Iberian Peninsula. This can be justified by a generalized public appreciation of exotic and unusual characteristics of invasive alien plants by these entities, promoting visual amenity (Carruthers *et al*., 2011; Dickie *et al*., 2014; Kueffer & Kull, 2017; Vaz *et al*., 2018).

People's attractiveness for specific attributes and traits exhibited by invasive alien plants seems to positively influence interest in visiting certain places (Cardoso *et al*., 2022; Lindemann-Matthies, 2016). For example, landscapes composed of invasive alien plants were of highest interest for visitation at times associated with the permanence of green leaves or the appearance of exuberant flowers, since these species stood out from the native plants (Vaz *et al*., 2019a). Conversely, landscape homogeneity resulting from the dominance of invasive alien plants can decrease visitation interest (Gaertner *et al*., 2014; Humair *et al*., 2014; Kueffer & Kull, 2017; Vaz *et al*., 2018). Likewise, heterogeneous and/or pristine landscapes with native settings may become more attractive and interesting compared to landscapes dominated by alien vegetation (Carruthers *et al*., 2011; Cordeiro *et al*., 2020; Kueffer & Kull, 2017; Vaz *et al*., 2018).

The presence of invasive alien plants in a landscape can also influence people's "sense of place", contributing changes in visitation patterns (Dickie *et al*., 2014; Kueffer & Kull, 2017; Le Maitre *et al*., 2011). On the one hand, invasive alien plants that have been introduced a long time ago can be perceived as elements of familiarity in the landscape, causing certain individuals and societies to become emotionally attached to these species (for example, appreciation of *Acacia dealbata* Link in Côte d'Azur, France) (Dickie *et al*., 2014; Kueffer & Kull, 2017; Kull *et al*., 2011; Lindenmann-Matthies, 2016; Niemiec *et al*., 2017). On the other hand, by transforming landscapes, these species can lead to the loss of the link between people and culturally valued ecosystems, reducing the desire to visit them (Carruthers *et al*., 2011; Le Maitre *et al*., 2011; Shackleton *et al*., 2007, 2019b). Also, the high productivity and rapid growth characteristic of invasive alien plants can make it difficult to practice recreational activities, particularly in riverine areas (e.g., blocking nautical transport) or close to infrastructure for this purpose (Vaz *et al*., 2017a).

In addition to the phenology of invasive alien plants and the landscape context where they occur, additional factors, such as accessibility and climate, are likely to drive visitation interest over invaded landscapes (Shackleton *et al*., 2019b; Vaz *et al*., 2019). Accessible areas (i.e., developed roads, rivers, and infrastructure) are associated with more opportunities for recreational and tourist activities, resulting in a higher visitor movement (Bachi *et al*., 2020; Plieninger *et al*., 2013; Tenerelli *et al*., 2016). Considering that invasive alien plants are prone to invade accessible areas, the likelihood of visiting areas with invasives increases (Figueroa-Alfaro & Tang, 2017; Vaz *et al*., 2019a).

Table 1 | Summary table of the potential contributions or disturbances of the presence of invasive alien plants to the interest of nature-based visitation.

	Contributions to visitation interest	
Presence of invasive alien plants	Increase	Decrease
Phenology	Exotic attributes can contribute to visual amenity as well as landscape re-green	Landscape homogeneity and degradation of recreational and tourist areas due to high productivity and rapid growth of invasive alien plants
Landscape context	Provision of “*sense of place*”, being perceived as elements of familiarity and symbolism of the landscape	Loss of "*sense of place*" and reduced cultural value of invaded landscapes
Accessibility	Increased contact between invasive alien plants and people in more accessible areas	Decreased contact between invasive alien plants and people in more accessible areas

Similarly, climatic factors that drive the distribution of invasive alien plants (Dullinger *et al*., 2017, Vicente *et al*., 2013, 2016), may overlap with those areas more prone for visitation, for instance due to mild temperatures. Accordingly, since nature-based visitation is dependent on the landscape context and the biodiversity present (Brambilla & Rochi, 2020; Plieninger *et al*., 2013; Zoderer *et al*., 2016), it may be particularly vulnerable to changes in the composition of invasive alien plants resulting from future climate change (Monz *et al*., 2021). In this sense, any geographic coincidence between invasive alien plants and nature-based tourism activities, are likely to shift with climate change (Monz *et al*., 2021).

Mapping visitation interest and the distribution of invasive alien plants can help in identifying areas where visitation interest coincides or not with the presence of invasive alien plant species, and hence developing more targeted strategies and practices that safeguard cultural services while restrict the expansion of invasive alien species.

1.4. Objectives

This thesis aims at identifying areas where the demand for cultural ecosystem services, expressed by visitation interest, coincides with the presence of invasive alien plant species.

To do so, three main questions were addressed:

1) Do the areas more prone to plant invasions coincide with those with higher visitation interest?

2) Are those spatial coincidences likely to change under future scenarios of climate change?

3) Which implications can those spatial coincidences bring to territorial management and planning?

These questions were tackled considering the North of Portugal as study area and three invasive alien trees as test species (*Acacia dealbata, Acacia longifolia* R.Br. and *Acacia melanoxylon* (Andrews) Wiild.

2. Material and methods

2.1. Study area

The study area comprises the North of Portugal, located in the Northwest of the Iberian Peninsula. It covers an area of 22876 km^2, characterized by the transition between the Euro-Siberian and the Mediterranean biogeographic realms (Aguiar *et al*., 2008). Thus, in the west and in the high-altitude areas of the Northeast, the climate is typically temperate Atlantic, with periods of high precipitation. On the other hand, in the valleys and plains of the eastern areas, the subcontinental Mediterranean climate predominates, characterized by drier periods (Aguiar *et al*., 2008). Average annual rainfall can range from 400mm in the easternmost areas to 2500mm or more in the higher western areas. The altitude in the North of Portugal can vary between 0 and 1545m. Regarding the geology of the area, the predominant rocks are granite and schist, making the soils more acidic. The geomorphology of North of Portugal is made up of distinct landscape units, namely mountain, riverside, and coastline (Aguiar *et al*., 2008) and, together with the variations in environmental conditions, result in a very heterogeneous area, rich in biodiversity, with different land uses revealed by a diverse vegetation cover.

The North of Portugal concentrates several areas with legal protection value belonging to the National Network of Protected Areas, most of which are integrated into the Natura 2000 Network of the European Union (EU) (ICNF, 2022), such as the Peneda-Gerês National Park, the Natural Park of Montesinho, Alvão, Douro Internacional and North Coast (ICNF, 2022). These parks are characterized by the natural, scenic, aesthetic, socio-economic, and cultural values they offer and aim at a sustainable interaction between human activities and the biodiversity present (ICNF, 2022).

The study area, due to its landscape heterogeneity, offers several resources for nature-based activities (Fernandes *et al*., 2020). For example, the westernmost regions through which the main rivers of the North flow, such as the Minho, Cávado, Ave and Douro rivers, are very popular for nautical activities such as "Stand Up Paddle", "Canyoning", "Canoeing" (Martins *et al*. al., 2021). In addition, activities such as "hiking" (e.g., *ecovias* and trails) are widely promoted throughout the area. The extensive coastline that covers the regions of Alto Minho, Cávado and the Porto metropolitan area is very popular for "Surfing", "Bodyboarding", among others (Martins *et al*., 2021). The

North of Portugal is also marked by a strong cultural component represented by archaeological monuments and historically relevant sites (Santarém *et al*., 2015).

On the other hand, the ecosystems present in the North of Portugal are heavily invaded by invasive alien species, since the climatic, topographical, and geomorphological characteristics mentioned above contribute to the invasibility of the landscape in the study area (Vicente *et al*., 2010, 2011, 2013).

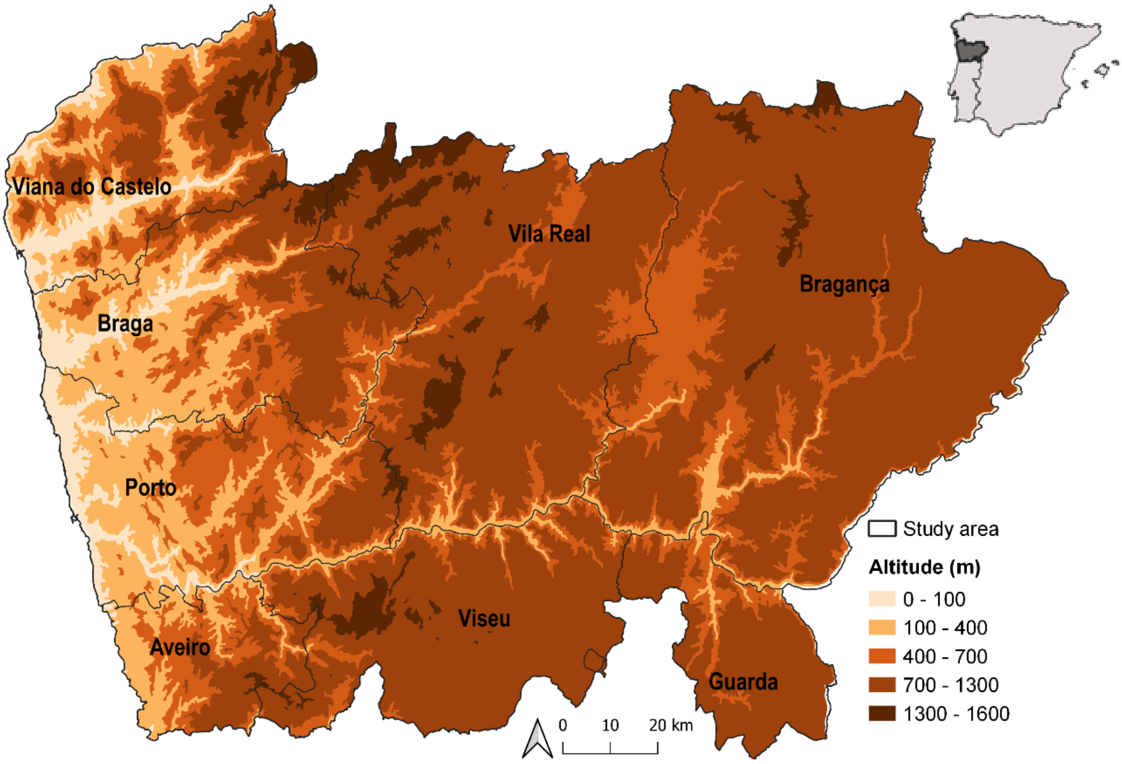

Figure 2 | (A) Map of the Nort of Portugal with the representation of the districts present in the area and (B) Location of the study area in the Iberian Peninsula context.

2.2. Test species

In this study three invasive alien trees were considered: *Acacia dealbata*, *Acacia melanoxylon* and *Acacia longifolia*, belonging to the family Fabaceae (*Leguminosae)*. These species are native to Australia and were introduced in Portugal during the 19th century and the beginning of the 20th century (Alves, 1858, cited by Vicente *et al*., 2019; Castroviejo *et al*., 1999, cited by Marchante *et al*., 2013) mainly for ornamental purposes, soil erosion control in coastal areas and soil fixation in forested areas (Fernandes *et al*., 2018; Lorenzo *et al*., 2010; Marchante *et al*., 2014). Currently, these species are considered the most prolific and well-documented invasive alien plant species in Portugal (Almeida & Freitas, 2006; César de Sá, *et al*., 2019; Lorenzo *et al*., 2010; Mouta *et al*., 2021; Vicente *et al*., 2011, 2013), threatening the composition of native flora communities and, consequently, strongly impacting the balance and functioning of natural ecosystems (Lorenzo *et al*., 2010; Marchante *et al*., 2008, 2011).

These three species have similar habitat requirements, produce large amounts of seeds which germination is stimulated by environmental disturbances, particularly fire, have high growth rates and very dense stands, which gives them a great capacity for invasion (Marchante *et al*., 2014). Moreover, populations of *A. dealbata and A. melanoxylon* present allelopathic effects (Hussain *et al*., 2020; Lorenzo *et al*., 2008; Marchante *et al*., 2014), that is, secondary chemical substances that, when released by the invasive alien plant species, can inhibit the growth and development of other plant species in the ecosystem (Hierro & Callaway, 2003; Hussain *et al*., 2020; Marchante *et al*., 2014). Thus, this allelopathic mechanism allows *A.dealbata* and *A. melanoxylon* to show dominance in colonized areas (Marchante *et al*., 2011, 2014). The most noticeable and common visual characteristic of the three invasive alien plant species corresponds to the yellow flowers they produce, from bright yellow (*A. dealbata* and *A. longifolia*) to pale yellow (*A. melanoxylon*) extremely associated to their ornamental value (Carruthers *et al*., 2011; Kueffer & Kull, 2017; Kull *et al*., 2011) (Figure 3).

In this way, in the last decades they have been expanding rapidly in Portugal, heavily populating mountainous and forest areas, road networks, watercourse banks (*A. dealbata , A. melanoxylon*) and coastal dunes (*A. longifolia*) (Marchante *et al*., 2011, 2014; Vicente *et al*., 2013). Among the three species, *A. dealbata* is currently the most wide-distributed species in the study area (Vicente *et al*., 2013).

Figure 3 | The three invasive alien plant species selected for this study, *Acacia dealbata* , *Acacia longifolia*, and *Acacia melanoxylon*. For each of the species, the first photograph represents a landscape invaded by the species and the second photograph illustrates the characteristic flowers of the species. All photographs depict locations in Portugal. Photos taken from http://invasoras.pt/.

2.3. Methodological framework

To investigate the spatial coincidences between the three *Acacia* species distributions and the visitation interest in North of Portugal, three main steps were followed (Figure 4). First, we assessed the distribution of visitation interest over natural settings in the study area, by collecting and mapping georeferenced photographs taken from the social media platform Flickr (Figure 4 – Step 1). Second, we evaluated the potential distribution *A. dealbata* , *A. longifolia*, and *A. melanoxylon* under current and future climate change scenarios for the North of Portugal (Figure 4 – Step 2). Finally, we quantified the spatial coincidences between *Acacia* distributions and visitation interest in the study area, under current and future climatic conditions (Figure 4 – Step 3).

2.3.1. Step 1 - Mapping cultural service visitation interest

We used georeferenced photographs from the social network Flickr (Flickr, 2022) to understand the distribution of visitation interest of sites in North of Portugal, as a proxy for cultural ecosystem services opportunities pertaining to visitation. We extracted the photographs from Flickr, through the "photosearcher" package (at: https://github.com/ropensci/photosearcher; Fox *et al*., 2020), using a bounding box with the coordinates of the study area in the R v. 4.1.3 program (R Core Team, 2022) with the Rstudio interface (Rstudio Team, 2022). Photographs were collected together with information on their location (coordinates) and date taken (Vaziri *et al*., 2020; Yoshimura & Hiura, 2017). A total of 113535 photos, from 2006 to 2022 were retrieved for the bounding box surrounding the study area. This set of photographs was then spatially projected in QGIS v.3.24.2 (QGIS, 2022) (represented by points) and only those photographs actually within the study area were considered, resulting in a final set of 97702 georeferenced photographs.

The final set of photographs was then overlaid with a 1km x 1km grid (UTM) using QGIS vector data management tools. Then, the number of photographs in each 1km^2 cell was counted and the number of photographs in each grid cell was then used as a measure of visitation interest in each cell. Considering the disproportionate number of photographs in each cell, we grouped the values obtained from the count into different classes using QGIS' data classification tools (QGIS, 2022). Thus, the quantile classification method was used, which groups the values into different intervals. The final map of visitation interest was classified into four classes: 0 (no apparent interest, grid cells where there are no photographs), 1 (lower interest), 2-4 (medium interest) and 5-1066 (higher interest). (Figure 4 - Step 1).

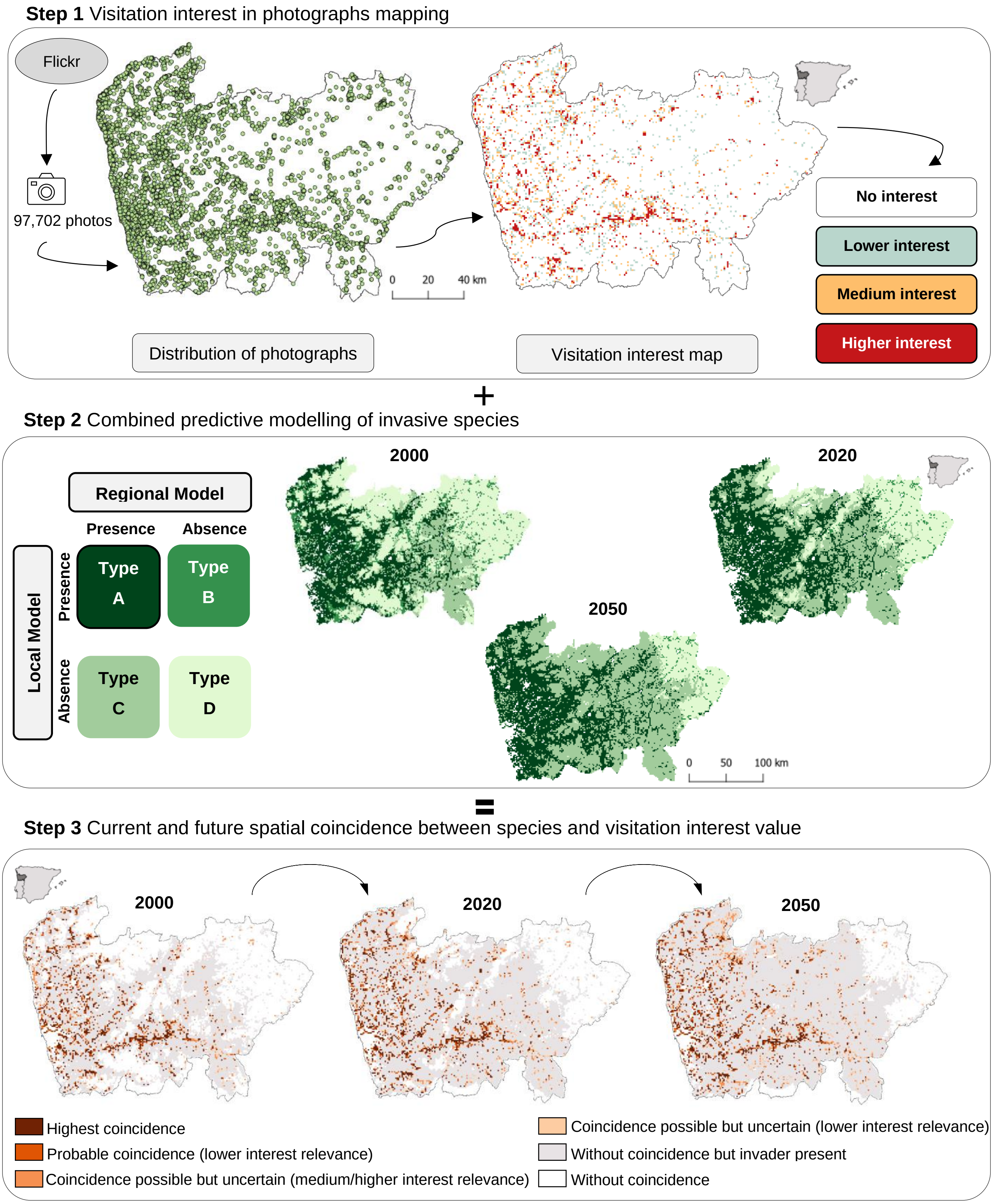

Figure 4 | Conceptual and analytical framework to predict current and future spatial coincidences between visitation interest and invasive alien species. The visitation interest was obtained and mapped by calculating the spatial distribution of georeferenced photographs for the study area, resulting in four classes from no interest to higher interest (Step 1). Current and future spatial distribution maps for the three invasive alien species (*Acacia dealbata* , *Acacia longifolia* and *Acacia melanoxylon*) obtained from Vicente *et al*. (2013), with the four predicted responses: (A) suitable regional conditions and local habitat, (B) only suitable local habitat, (C) only suitable regional conditions, and (D) unsuitable regional conditions and local habitat (Step 2). Final maps of the spatial coincidences between visitation interest and the predicted distribution of the three invasive alien species (A-D) for 2000, 2020 and 2050. Adapted from Vicente *et al*. (2013).

2.3.2. Step 2 - Current and future spatial potential distributions of invasive alien plant species

The maps of the current and future potential distribution of *A. dealbata* , *A. longifolia and A. melanoxylon* were obtained from Vicente *et al*. (2013). In this study, the authors used a combined predictive approach to develop projections of the current and future distributions of the three *Acacia* species. This approach allowed the development of partial species distribution models with subsets of regional and local information as predictors (Vicente *et al*., 2011; 2013). These partial models were developed with the same response variables (presence/absence of the species), for the same spatial extent and using the same grain size. The combined prediction models were calibrated and projected using the BIOMOD R package (Thuiller *et al*.,2009) and, for each of the species, the final model was obtained by spatial overlaying the predictions of the regional and local partial models (Vicente *et al*., 2011, 2013). This technique allowed to obtain more informative results (Guisan & Thuiller, 2005; Pearson *et al*., 2004). The authors selected environmental variables based on their importance to the ecology and distribution of target species. Environmental variables were grouped into eight ecological types, namely climate, dispersal corridors, geology, landscape composition, landscape structure, fire regimes, phenological and productivity metrics (Vicente *et al*., 2013). Furthermore, the environmental variables used were classified according to their spatial scale of variation (regional or local). Thus, environmental predictors related to climate contributed to calibrate the regional models, while the remaining predictors were used to calibrate the local models, for each species (Vicente *et al*., 2013). The predicted presence and absence combinations (for regional and local partial model results) were classified into four responses: A- suitable regional conditions and local habitat, B- suitable local habitat only, C- suitable regional conditions only and D- unsuitable regional conditions and local habitat (Figure 4 – Step 2).

From the climatic scenarios applied in the study, we just considered the A1B scenario, as it generated more pronounced results in the distribution of the three *Acacia* species in Vicente *et al*. (2013). This scenario is represented by very rapid economic growth stimulated by increasing globalization, a balance in the use of fossil and non-fossil energy, and by high temperature increases, ranging from 1.4 to 6.4 ºC (Nakicenovic & Swart, 2000).

2.3.3. Step 3 - Mapping spatial coincidences between visitation interest and invasive alien plant species

We used the visitation interest distribution map and the spatial projections of the distribution of the three *Acacia* species to calculate potential spatial coincidences between the invasive alien plant species distribution and the cultural ecosystem services in a Geographic Information System software, QGIS v.3.24.2 (QGIS, 2022). Through the processing tools of QGIS, "raster calculator", the data of the visitation interest were overlaid with the data from spatial projections of invasive alien plant species distribution. The final maps of the spatial potential coincidences were obtained by adding the number of classes of both maps occurring in each cell. The results were represented in combinations of the potential spatial coincidences between the invasive alien plant species predictions and the visitation interest distribution map (Figure 5, a-f):

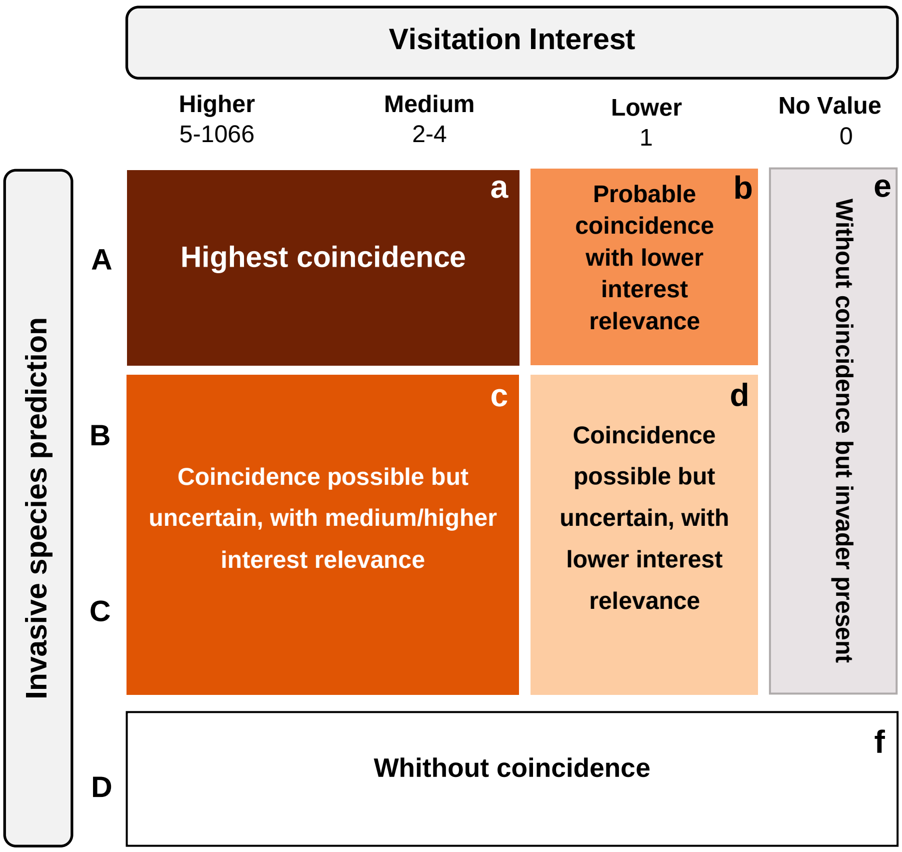

Figure 5 | Results of possible spatial coincidences combinations between the visitation interest distribution map and the invasive alien plant species predictions: (a) areas of highest coincidence, (b) areas of probable coincidence with lower interest relevance, (c) areas of coincidence possible but uncertain, with medium or higher interest relevance, (d) areas of coincidence possible, but uncertain, with lower interest relevance, (e) areas without coincidence, but with the presence of invasive species and (f) areas without coincidence. Adapted from Vicente *et al*. (2013).

a) Highest coincidence, where the visitation interest is higher or medium, and the invasive alien plant species has suitable regional conditions and local habitats available (type A);

b) Probable coincidence with lower interest relevance, where the visitation interest is lower, and the invasive alien plant species has suitable regional conditions and local habitats available (type A);

c) Coincidence possible but uncertain with interest relevance, where the visitation interest is medium or higher and the invasive alien plant species has only suitable regional conditions or local habitats available (type B or C);

d) Coincidence possible but uncertain with lower interest relevance, where the visitation interest is lower, and the invasive alien plant species has only suitable regional conditions or local habitats available (type B or C);

e) Without coincidence (no visitation interest), but with the invasive alien plant species is expected to be present (type A, B or C);

f) Without coincidence.

The total area (km^2) of the spatial coincidence between the visitation interest and the three invasive alien plant species for each combination (a-f) was calculated. We then obtained nine final maps of possible current and future spatial coincidences between visitation interest and invasive alien plant species under a climate change scenario, corresponding to the years 2000, 2020 and 2050 for each of the *Acacia* species.

3. Results

3.1. Visitation patterns in the study area

The spatial distribution of visitation interest, expressed by the mapping of Flickr georeferenced photographs in the study area is presented in Figure 6. In general, the highest levels of visitation interest were found distributed in the easternmost portion of the study area, along the Douro river, and around cities and villages (e.g., Viana do Castelo, Braga, Porto). By contrast, lower visitation interest was observed in the interior (westernmost) region of the North of Portugal, with the exception of main cities such as Bragança. There was no photographic data for an extensive area of the North of Portugal (No interest = 18507 km^2). On the other hand, significantly smaller areas corresponded to sporadic visitation interest (lower to medium interest: 1191 km^2 and 894 km^2, respectively). Only a small portion of the study area showed higher visitation interest (higher interest = 800 km^2) (Table 1).

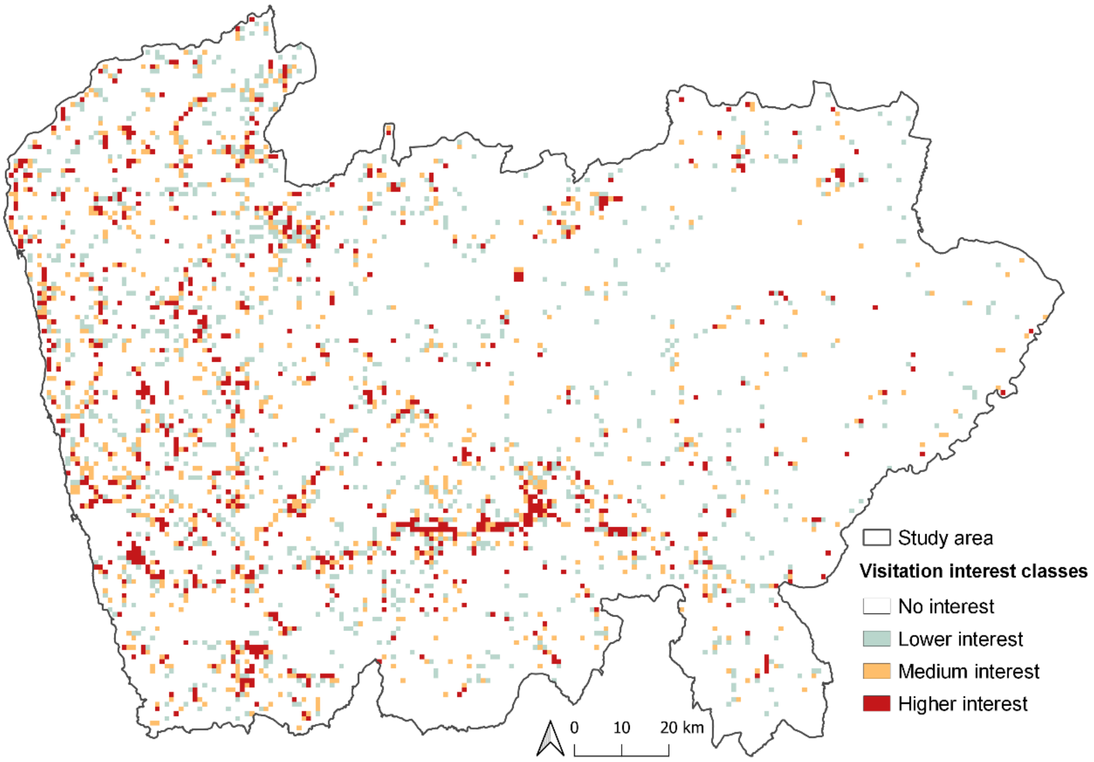

Figure 6 | Map of the spatial distribution of the four visitation interest classes for the North of Portugal: No interest, Lower interest, Medium interest and Higher interest.

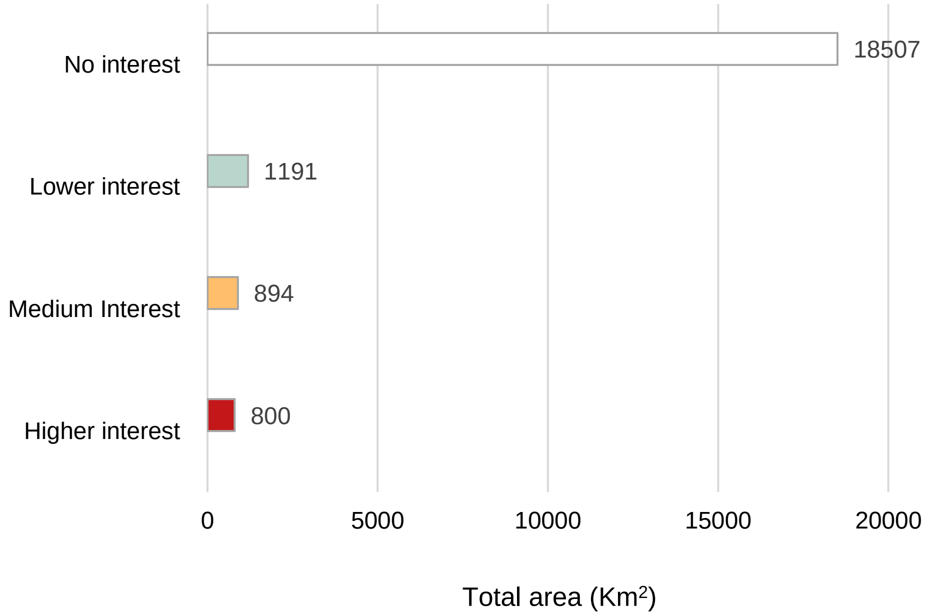

Figure 7 | Number of km^2 of each of the four visitation interest classes and the corresponding range of photographs per grid cell (No interest: 0; Lower interest: 1; Medium interest: 2 to 4; Higher interest: 5 to 1066) for the area of study.

3.2. Spatial coincidence between visitation interest and invasive alien plant species under current and future climate change scenario

Potential spatial coincidences between visitation interest and invasive alien plant species varied between the three *Acacia* species and over time (Figure 7, Figure 8, and Figure 9).

Regarding *A. dealbata* , all spatial combinations that reveal coincidence or possibility of coincidence (a-d) between the invasive species and the visitation interest tended to increase from 2000 to 2050 (Highest coincidence: **2000 = 959 km^2, 2020 = 1103 km^2, 2050 = 1116 km^2** ; Probable coincidence with lower interest relevance: 2000 = 549 km^2, 2020 = 632 km^2, 2050 = 641 km^2 ; Coincidence possible but uncertain with medium or higher interest relevance: **2000 = 386 km^2, 2020 = 451 km^2, 2050 = 527 km^2** ; Coincidence possible but uncertain with lower interest relevance: 2000 = 293 km^2, 2020 = 397 km^2, 2050 =499 km^2) (Table 2). In the same way, areas classified as without coincidence but with the presence of the species (e) were predicted to increase between 2000 and 2050 (2000 = 10379 km^2, 2020 = 13878 km^2, 2050 = 16086 km^2).

On the other hand, areas considered without coincidence (f) showed a tendency to decrease over time (2000 = 8826 km^2, 2020 = 4931 km^2, 2050 = 2523 km^2) (Table 2).

For *A. longifolia*, the dynamics of spatial coincidence with visitation interest were mostly opposite to those of *A. dealbata* . For this species, the spatial coincidence changes for all combinations were very slight over time, with the most significant occurring between 2000 and 2020 (Table 3). Areas of highest coincidence and probable coincidence with lower relevance of interest (a-b) showed a decrease with time ((a): 2000 = **218 km^2**, 2020 = **23 km^2** ; (b): 2000 = 118 km^2, 2020 = 8 km^2), and for 2050 it was predicted that there would be no spatial coincidence between the species and the visitation interest, for both combinations. Areas with uncertain possibility of coincidence with medium or higher relevance of interest and lower relevance of interest (c-d) were predicted to decrease between 2000 and 2020 ((c): **2000= 438 km^2, 2020 = 335 km^2** ; (d): 2000 = 234 km^2, 2020 = 179 km^2), but showed with a slight increase in 2050 ((c): 343 km^2 ; (d): 186 km^2). Areas without coincidence, but with the presence of species (e) tended to decrease over time (2000 = 3171 km^2, 2020 = 1947 km^2, 2050 = 1937 km^2). However, areas without spatial coincidence (f) were predicted to increase until 2050 (2000 = 17213 km^2, 2020 = 18908 km^2, 2050 = 18926 km^2) (Table 3).

The spatial coincidences between the visitation interest and *A. melanoxylon* showed different dynamics over time and the most significant changes occurred between 2020 and 2050, contrary to *A. longifolia* (Table 4). Areas of highest coincidence or probable coincidence with lower relevance of interest (a-b) were predicted to decrease between 2000 and 2050 ((a): 2000 = **742 km^2**, 2020 = **607 km^2**, 2050 = **333 km^2** ; (b): 2000 = 423 km^2, 2020 = 362 km^2, 2050 = 187 km^2). However, areas of possible but uncertain coincidence with medium or higher relevance of interest and with lower relevance of interest (c-d) tended to increase over time ((c): **2000 = 304 km^2, 2020 = 427 km^2, 2050 = 629 km^2** ; (d): 2000 = 207 km^2, 2020 = 275 km^2, 2050 = 396 km^2). A slight increase was predicted between 2000 and 2020 (6247 km^2 and 6484 km^2, respectively), followed by a small decrease to 2050 for areas without coincidence (6330 km^2) but with the presence of the species (e) and, conversely, areas without coincidence (f) tended to decrease slightly between 2000 and 2020 (13469 km^2 and 13237 km^2, respectively) and increase between 2020 and 2050 (2050 = 13517 km^2) (Table 4).

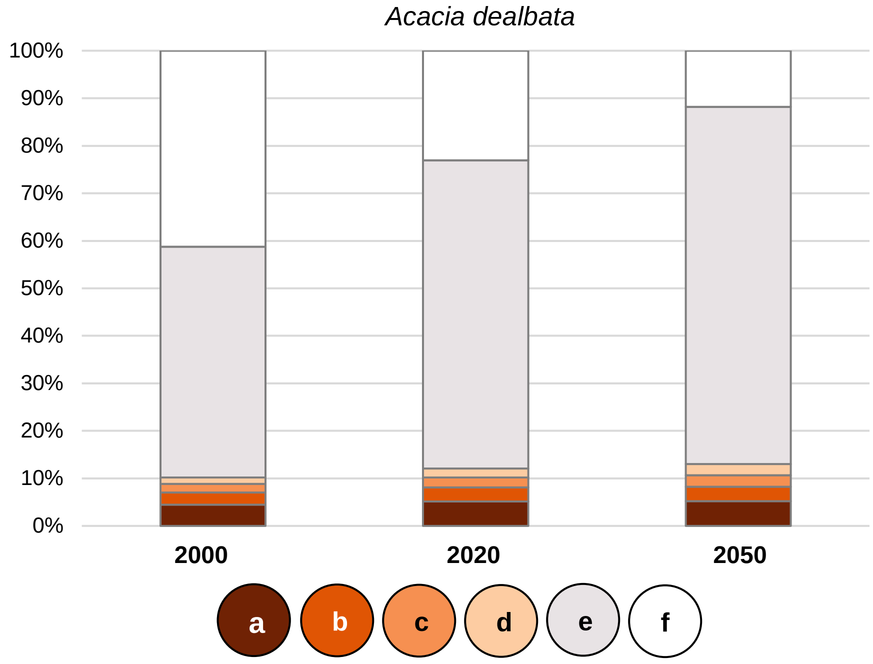

Figure 8 | Percentage of the number of km^2, out of a total of 21329 km^2, for each of the combinations of spatial coincidence between *A. dealbata* and the visitation interest, for each year (2000, 2020 and 2050): (a) Highest coincidence, (b) Probable coincidence with lower relevance of interest, (c) Coincidence possible but uncertain with medium/higher relevance of interest, (d) Coincidence possible but uncertain with lower relevance of interest, (e) Without coincidence, but with the presence of the species and, (f) Without coincidence.

Table 2 | Potential spatial coincidences between the predicted spatial distribution of *Acacia dealbata* and the visitation interest map. For each year (2000, 2020 and 2050) the number of km^2 resulting from the spatial coincidence between the classes of *A. dealbata* and the classes of visitation interest for each combination is represented: (a) Highest coincidence (response A and interest value between 2 to 1066), (b) Probable coincidence with lower relevance of interest (response A and value of interest 1), (c) Possible but uncertain coincidence with medium/higher relevance of interest (response B or C and interest value between 2 to 1066), (d) Possible but uncertain coincidence with lower relevance of interest (response B or C and interest value 1), (e) Without coincidence but with the presence of the species (response A, B or C and no value of visitation interest) and, (f) Without coincidence.

	2000	**2020**	**2050**
a | Highest coincidence	**959**	**1103**	**1116**
b | Probable coincidence (lower interest relevance)	549	632	641
c | Coincidence possible but uncertain (medium/higher interest relevance)	**386**	**451**	**527**
d | Coincidence possible but uncertain (lower interest relevance)	293	397	499
e | Without coincidence but invader present	10379	13878	16086
f | Without coincidence	8826	4931	2523

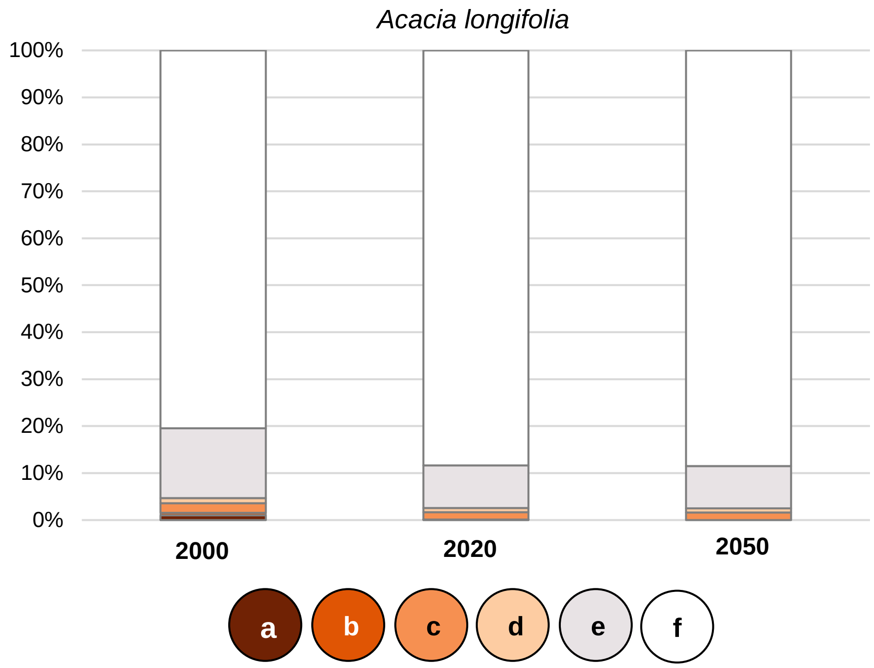

Figure 9 | Percentage of the number of km^2, out of a total of 21329 km^2, for each of the combinations of spatial coincidence between *A. longifolia* and the visitation interest, for each year (2000, 2020 and 2050): (a) Highest coincidence, (b) Probable coincidence with lower relevance of interest, (c) Coincidence possible but uncertain with medium/higher relevance of interest, (d) Coincidence possible but uncertain with lower relevance of interest, (e) Without coincidence, but with the presence of the species and, (f) Without coincidence.

Table 3 | Potential spatial coincidences between the predicted spatial distribution of *Acacia longifolia* and the visitation interest map. For each year (2000, 2020 and 2050) the number of km^2 resulting from the spatial coincidence between the classes of *A. longifolia* and the classes of visitation interest for each combination is represented: (a) Highest coincidence (response A and interest value between 2 to 1066), (b) Probable coincidence with lower relevance of interest (response A and value of interest 1), (c) Possible but uncertain coincidence with medium/higher relevance of interest (response B or C and interest value between 2 to 1066), (d) Possible but uncertain coincidence with lower relevance of interest (response B or C and interest value 1), (e) Without coincidence but with the presence of the species (response A, B or C and no value of visitation interest) and, (f) Without coincidence.

	2000	2020	2050
a | Highest coincidence	**218**	**23**	**0**
b | Probable coincidence (lower interest relevance)	118	8	0
c | Coincidence possible but uncertain (medium/higher interest relevance)	**438**	**335**	**343**
d | Coincidence possible but uncertain (lower interest relevance)	234	179	186
e | Without coincidence but invader present	3171	1947	1937
f | Without coincidence	17213	18908	18926

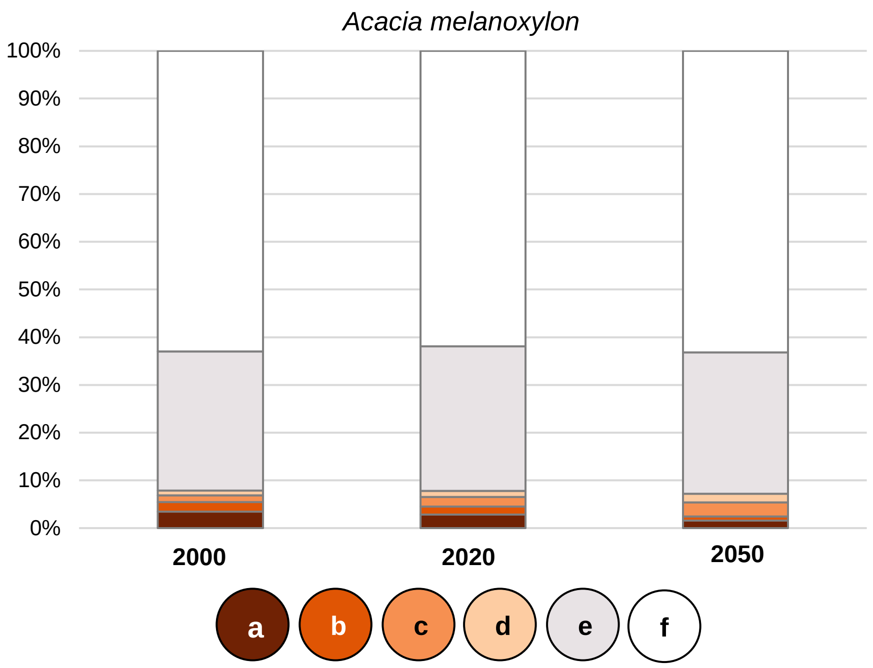

Figure 10 | Percentage of the number of km^2, out of a total of 21329 km^2, for each of the combinations of spatial coincidence between *A. melanoxylon* and the visitation interest, for each year (2000, 2020 and 2050): (a) Highest coincidence, (b) Probable coincidence with lower relevance of interest, (c) Coincidence possible but uncertain with medium/higher relevance of interest, (d) Coincidence possible but uncertain with lower relevance of interest, (e) Without coincidence, but with the presence of the species and, (f) Without coincidence.

Table 4 | Potential spatial coincidences between the predicted spatial distribution of *Acacia melanoxylon* and the visitation interest map. For each year (2000, 2020 and 2050) the number of km^2 resulting from the spatial coincidence between the classes of *A. melanoxylon* and the classes of visitation interest for each combination is represented: (a) Highest coincidence (response A and interest value between 2 to 1066), (b) Probable coincidence with lower relevance of interest (response A and value of interest 1), (c) Possible but uncertain coincidence with medium/higher relevance of interest (response B or C and interest value between 2 to 1066), (d) Possible but uncertain coincidence with lower relevance of interest (response B or C and interest value 1), (e) Without coincidence but with the presence of the species (response A, B or C and no value of visitation interest) and, (f) Without coincidence.

	2000	**2020**	**2050**
a | Highest coincidence	**742**	**607**	**333**
b | Probable coincidence (lower interest relevance)	423	362	187
c | Coincidence possible but uncertain (medium/high interest relevance)	**304**	**427**	**629**
d | Coincidence possible but uncertain (lower interest relevance)	207	275	396
e | Without coincidence but invader present	6247	6484	6330
f | Without coincidence	13469	13237	13517

The maps resulting from the combinations of spatial coincidences between the three invasive alien plants and the visitation interest showed that the main potential coincidences occurred in the western zone under current climatic conditions, more precisely along the coastal area of the North of Portugal. The largest area of coincidence with visitation interest was predicted to occur for *A. dealbata* , with spatial dynamic of coincidence covering the coastal zone and part of the central zone of the study area between 2000 and 2020 (1-2, Figure 10). On the other hand, *A. longifolia* was predicted as the species with the smallest area of spatial coincidence with visitation interest. The spatial patterns of coincidence for this species were mainly concentrated in the coastal zone of the study area and showed a decrease in the area of highest spatial coincidence between the years 2000 and 2020 (4-5, Figure 10). *A. melanoxylon* was predicted as the second study species with the highest area extension coinciding with the visitation interest, from the coastal zone to the central zone of the study area. The spatial coincidence dynamics for *A. melanoxylon* varied slightly between 2000 and 2020, with areas of highest spatial coincidence decreasing, mainly in the northwestern part of northern Portugal (7-8, Figure 10).

Additionally, the maps obtained revealed that the areas of spatial coincidence between *A. dealbata* and the visitation interest could increase by 2050, under future climatic conditions, with a potential expansion of these areas to the interior zone of the North of Portugal (3, Figure 10). In contrast, for both *A. longifolia* and *A. melanoxylon* the dynamics of spatial coincidence with visitation interest were predicted to vary slightly in the future. Regarding *A. longifolia*, it was predicted that areas of highest spatial coincidence may not exist in 2050 (6, Figure 10). On the other hand, the areas of highest spatial coincidence between *A. melanoxylon* and the visitation interest were predicted to intensify in the coastal zone of the study area by 2050, contrary to the central zone (9, Figure 10).

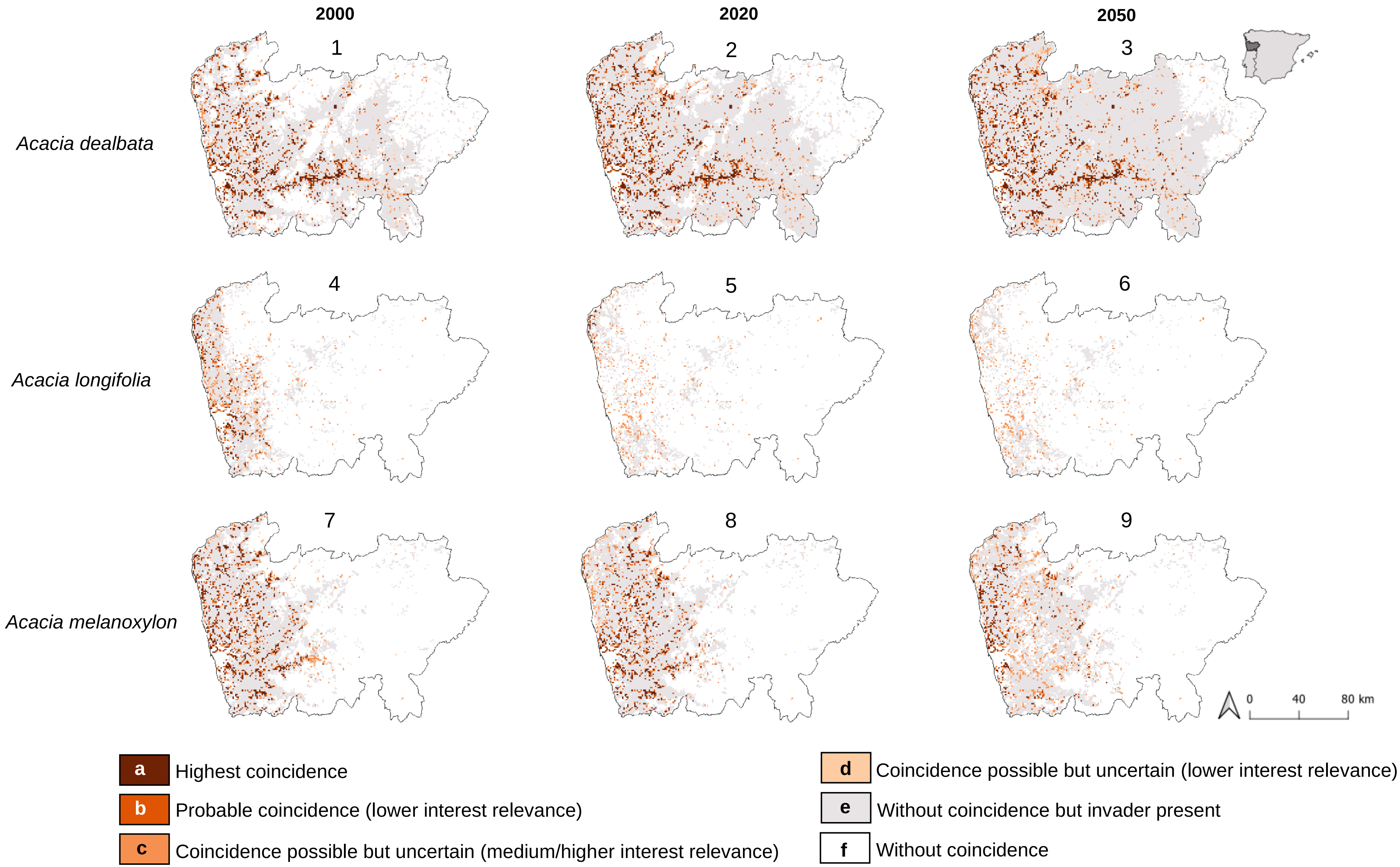

Figure 11 | Maps resulting from the spatial coincidences between the invasive alien plants predictions and the visitation interest map for the three study species: *Acacia dealbata* , *Acacia longifolia* and *Acacia melanoxylon* for the year 2000 and with a future climate scenario (A1B) for 2020 and 2050.

4. Discussion

In this study, we described an approach to investigate potential current areas of spatial coincidence between three invasive alien plant species and visitation interest for North of Portugal and assessed their future spatial distribution under a climate change scenario. To this end, we collected georeferenced photographs from the social networking platform Flickr to map visitation patterns expressed as a gradient of interest in the study area. Additionally, we used current and future distribution models of three *Acacia* species produced by Vicente *et al*. (2013) to overlap with the visitation interest map. Overall, the approach used allowed us to identify areas of potential spatial coincidence, mainly in the coastal and central areas of the North of Portugal. Furthermore, we revealed that *Acacia dealbata* was the species that presented the largest area of spatial coincidence with visitation interest, increasing with time, compared to the other species studied.

4.1. Spatial distribution of visitation interest

We assumed the presence of photographs in an area as a visitation proxy (Toivonen *et al*., 2019). Thus, the application of georeferenced metadata, from Flickr and to the limits of the study area, allowed to obtain spatial patterns of visitation interest in the North of Portugal. Considering that publications on Flickr present geographic coordinates automatically generated by the devices, it was possible to obtain the location where the photos were taken (Toivonen *et al*., 2019). Some studies have proven the effectiveness of using geographic information from social media photographs to track visitor movement in areas intended for nature-based recreation (Sonter *et al*., 2016; Tenkanen *et al*., 2017; Wood *et al*., 2013). Counting the photographic data for each 1 km^2 area and grouping them into classes of visitation interest allowed us to understand the density of photographs and their spatial distribution in the study area. This is relevant as higher volumes of photo posts on social media platforms referring to a particular location tend to be associated with higher levels of popularity for that location (Fisher *et al*., 2018; García-Palomares *et al*., 2015; Heikinheimo *et al*., 2017; Levin *et al*., 2017; Wood *et al*., 2013).

Our results showed that areas corresponding to higher visitation interest, hence a higher density of photographs, were not randomly distributed in the study area, but instead were constricted to specific locations. This reveals that there are hotspots for providing opportunities for cultural services in North of Portugal, compared to larger areas where the visitation interest is very low or null. Since physical attributes of the landscape influence the visitation interest, the location of these hotspots may correspond to places where the presence of bodies of water (e.g., rivers, lakes, sea) is higher (coastal zone) and in areas with high protection value present throughout the study area and which are normally associated with a greater offer of cultural services (Pastur *et al*., 2016). On the other hand, areas where there was no visitation interest or the visitation interest was lower were mostly concentrated in the interior of the North of Portugal, where the places may be less accessible on the ground (for example, fewer roads or footpaths). As already shown in previous studies, accessibility is a determining factor in enjoying cultural services, such as recreation and ecotourism (Pastur *et al*., 2016; Richards & Friess, 2015; Vaz *et al*., 2019a; 2020).

In addition to the spatial distribution, the use of georeferenced photographs between 2006 and 2022 aimed to aggregate more significant temporal information about visitation in the study area, since the volume of published photographs may vary in different years (Fisher *et al*., 2018; Tenkanen *et al*., 2017; Toivonen *et al*., 2019).

4.2. Current and future coincidences between visitation interest and invasive alien plants in North of Portugal

The results of the current potential coincidences showed that *A. dealbata* was the species with the highest presence in areas where the visitation interest was higher. This may be since this invasive alien plant is the most widely distributed in North of Portugal (César de Sá *et al*., 2019; Vicente *et al*., 2013) and, consequently, more likely to be at places where visitation occurs (Marchante *et al*., 2017; Shackleton *et al*., 2016, 2019b). The areas of spatial coincidence were distributed a little throughout the coastal and central zone, where the concentration of dispersion corridors (e.g., rivers, roads, pedestrian paths) is greater, which can enhance the contact between people and the species and increase the invader's contributions to visitation (Marchante *et al*., 2017; van Berkel *et al*., 2018; Vaz *et al*., 2019a,b; Vicente *et al*., 2013).

It was possible to observe that the area of spatial coincidence between the visitation interest and *A. dealbata* followed the expansion of the invasive species over time to the easternmost zone of the study area, mainly towards protected areas such as the Penêda-Gerês area (Vicente *et al*., 2013). Areas under a protection regime are highly sought after for recreational activities and aesthetic values (Cardoso *et al*. 2022), and as previously suggested by Vaz *et al*., (2018) invasive alien plants can contribute to landscape aesthetics and nature-based activities in the protected area, particularly in accessible areas. Transposing these insights to the remaining area of study, the location of cultural hotspots (captured by the visitation interest) seems to coincide broadly with the areas of *A. dealbata* occurrence, which may potentially reflect the contributions of the species to visitation. Since *A. dealbata* was introduced in Portugal mainly for ornamental use, its physical attributes may be contributing to the attractiveness of the landscape and, consequently, increasing people's interest in these areas (Fernandes, 2018; Vaz *et al*., 2019a).

Under a future scenario of climate change, the areas of spatial coincidence between the visitation interest and *Acacia* invasions seem to increase, a pattern mostly reflected by the predicted expansion of *A. dealbata* in the coming decades (Vicente *et al*., 2013). However, our results showed large areas where there was no apparent visitation interest, that is, there was no spatial coincidence, but the species is present and tended to increase in the future. This may be due to the limitation of our methodology, but also to the fact that the increase in colonization by *A. dealbata* is expected to occur in the innermost area of the North of Portugal, where accessibility is also lower, therefore lower visitation.

Regarding *A. longifolia* and *A. melanoxylon*, the decrease in areas coincident with visitation interest over time may be because the expansion of these species to the study area was predicted to decrease slightly in the future (Vicente *et al*., 2013). As *A. longifolia* and *A. melanoxylon* showed smaller dispersal areas than *A. dealbata* , these species may not be so easily perceived mainly in the eastern and interior areas of the North of Portugal (Vaz *et al*., 2019b). The coastal zone of the study area concentrated the areas of highest spatial coincidence of visitation interest with the presence of *A. longifolia*, and this can be explained by the fact that the species was introduced in Portugal to control dune erosion and, as such, have essentially dissipated coastal ecosystems (Marchante *et al*., 2008, 2015).

Overall, the visitation interest seemed to accompany the propagation of the three invasive species in the study area, which may reveal potential interactions contributions to cultural services. Furthermore, *A. dealbata* seemed to be the most valued species by people in North of Portugal. However, in the future and under climate change scenarios, our results demonstrated that the direction of public preferences based on visitation may change, especially for *A. longifolia* and *A. melanoxylon,* as factors related to invasiveness may potentiate their expansion (Vicente *et al*., 2013) and influence visitation patterns in the North of Portugal.

4.3. Implications for the management of visitation interest and invasive alien plants

The mapping of georeferenced photographs from Flickr allowed the identification of areas where the opportunities for cultural services, through visitation interest, may be greater (cultural hotspots) and large areas with lower or no provision of cultural services in the North of Portugal. Thus, understanding that cultural service hotspots are mostly concentrated in the coastal and central area of the study area and that places with lower public visitation are in the innermost eastern area, could help policymakers to implement more effective landscape management measures in the North of Portugal. In this sense, the most valued areas for visitation can be optimized, for example, through the improvement and maintenance of accesses and infrastructure, contributing to enhance the recreational experiences of visitors. On the other hand, the innermost area of the North of Portugal can be developed by investing in the construction of infrastructure and accessibility that promote tourism and nature-based visitation in rural areas (Cabana *et al*., 2020; Plieninger *et al*., 2013; 2015).

Additionally, the mapping of spatial coincidences between the visitation interest and invasive alien plants indicated that in the North of Portugal, hotspots of cultural services correspond to areas with a strong presence of *Acacia* species, mainly *A. dealbata* , and that these coincidences are significant, depending on people's perception of the species. Understanding how people interact with invasive alien plants in a spatially explicit way can contribute to the implementation of more integrative invasive alien plant species management measures at the national level (Dickie *et al*., 2015; Vaz *et al*., 2019a). For example, prioritizing landscapes and ecosystems where these species occur and, at the same time, more prone to nature-based visitation, such as the coast, on the periphery of urban areas and in natural and protected areas; reinforce control and preservation measures in areas of spatial coincidence between people and invasive alien plants, especially for *A. dealbata*; promote environmental awareness and education actions in areas where there is greater contact between people and invasive alien plants.

Considering that current and future environmental changes may alter the behavior of invasive alien species and their impacts on ecosystems (Vicente *et al*., 2013, 2016) and consequently change people's attitudes towards these species (Shackleton *et al*., 2015, 2016), our methodology allowed a spatial-temporal analysis of these potential changes in the future for an extensive area such as the North of Portugal. Thus, anticipating the spatial distributions of cultural services and invasive alien plants in landscapes and how the interactions between people and nature are processed will allow the formulation of efficient, more economical, and justified management and conservation measures not only for the North of Portugal, but for any ecosystem or landscape.

4.4. Methodological improvements and constraints

Although the methodology used in this thesis is innovative to investigate how the distribution of cultural services is influenced by the dispersion of invasive species, there are some limitations and improvements that need to be addressed.

First, our study was reproduced only for three species of *Acacia*, however more species could have been considered. In recent decades, numerous species of invasive alien plants have been reported in Portugal (Marchante *et al*., 2014; Morais *et al*., 2017), with *Carpobrotus edulis, Oxalis pes-caprae, Cortaderia selloana* or even *Hakea sericea* representing representing widely distributed species in the study region (Marchante *et al*., 2014). Since different invasive alien species can trigger different contributions to cultural ecosystem services, such as visitation (Shakleton *et al*., 2019b), including a larger number of test species could allow a more informed understanding of the interactions between species and nature-based activities.

Second, although compared to other social media platforms, Flickr is a suitable source of data to infer on visitation interest associated to attributes of ecosystems and biodiversity (Gliozzo *et al*., 2016; Hausmann *et al*., 2017), the approach shown here did not allow the assessment of the type of cultural contributions associated to the prevalence of a higher number of photos (or visitation interest) at each location, nor the reasons for visiting those locations. To this end, the qualitative and quantitative analysis of the photographic content would make it possible to describe the categories of services displayed in the content of each photograph (e.g., landscape, nature, species, recreational activities) (Cardoso *et al*., 2022; Hausmann *et al*., 2017; Toivonen *et al*., 2019; Vaz *et al*., 2020). For that reason, as well, it was not possible to have an idea of the type of surrounding landscape/ecosystem, that is, whether they corresponded to urban or non-urban areas.

Third, we keep in mind that inferring visitation interest from social media platforms will inevitably only capture the universe of people that actually use those platforms (i.e, the social media users; Toivonen *et al*., 2019). Generally, users of social networking platforms are associated with specific social and demographic groups, i.e., younger, educated, and higher-income people (Kemp, 2018 cited by Toivonen *et al*., 2019;

Tenerelli *et al*., 2016), which can result in biased data sourced from Flickr. Furthermore, people use different platforms and means to communicate and show their interest on locations and nature, and as such, the visitation interest captured in this methodology only reflect a small portion of the visitor population (Hausmann *et al*., 2017). At the same time, not only did Flickr's popularity decline, but there was also a potential loss of photographs from the platform over time (Zhang *et al*., 2020). Consequently, the areas classified as "no interest" that were obtained in this work may not reflect the reality of visitation interest, as a result of the limitations mentioned above. Thus, further data sources, including other social media platforms but also, for instance, citizen science data or socio-economic statistics could act as complementary approaches allowing to obtain more realistic and complete results (Di Minin *et al*., 2015; Hausmann *et al*. 2017).

Fourth, given that landscape attributes can influence people's perceptions of cultural services (Pasteur *et al*., 2016; Vaz *et al*., 2020), would be important to apply data from Geographic Information Systems (GIS) and satellite data to infer about accessibility (e.g. pedestrian paths, roads), landscape context (e.g. diversity of colors, heterogeneity) and tourist attractions (e.g. cultural and historical heritage, activities recreational activities), which are usually more valued by people (Pasteur *et al*., 2016; Tieskensa *et al*., 2018; Vallecillo *et al*., 2019). For an area like the North of Portugal where different landscape mosaics can be found and where distinct cultural landscapes are present, mapping landscape values that translate into public preferences would be important (López-Santiago *et al*., 2014; Plieninger *et al*., 2013; Ridding *et al*., 2018; López-Santiago *et al*., 2014).

Fifth, a series of factors contribute to the differences in the intangible meanings that people associate with cultural services and the nature that surrounds them, and the analysis of photographic content does not allow us to obtain this more subjective information. However, since users tend to add captions and tags to their posts on social media, applying “multimodality” (Toivonen *et al*., 2019), that is, combining visual and textual analysis (Ramachandram & Taylor, 2018) may improve the methodology, as it may provide additional information regarding the sensations and motives that led an individual to capture a certain attribute of the environment (Toivonen *et al*., 2019; You *et al*., 2016).

Finally, human activities represent dynamic processes that change spatially, and temporally as environmental and landscape scenarios change. For this reason, using modelling procedures, such as those used to predict species distributions, would allow not only to explain the distribution of cultural services in each area, but also to anticipate their distributions in future and changing scenarios, relating the presence of cultural services with environmental and landscape variables (Clemente *et al*., 2019; Otero-Rozas *et al*., 2016; Richards & Friess, 2015, Yoshimura & Hiura, 2017).

Our methodology was not able to explain the different perceptions that lead people to evaluate invasive alien plants and their role in cultural services, even so, it will provide justification for future work.

5. Conclusion

Biological invasions represent sociological processes, and the impacts they cause on ecosystems and the way they change them are dependent on the perceptions of different social sectors (Vaz *et al*., 2017a,b). Global political agendas increasingly recognize the urgency of adopting strategies to slow the spread of biological invasions and manage their potential impacts (Brunel *et al*., 2013; Genovesi *et al*., 2013; IPBES, 2019). An example of this is the integration of the management of invasive alien species in the “2030 action targets” stipulated by the Convention on Biological Diversity (CBD) Strategic Plan for Biodiversity the Post-2020 Global Biodiversity Framework from the Convention on Biological Diversity (CBD) (CBD, 2020). However, these goals are progressing very slowly or not at all (Tittensor *et al*., 2014). In part, this may be because decision-making regarding the management of invasive alien species does not consider the social dimension (Abrahams *et al*., 2019; Estévez *et al*., 2014; Kueffer, 2017; Vaz *et al*., 2017b).

In this study, we investigate how cultural services can be shaped by the invasion of alien plant species in spatial and temporal contexts, since cultural services are the most directly experienced by people, reflect the intrinsic interactions between them and the environment and, therefore, are essential for human well-being. The application of social media data together with projections of current and future distributions of three *Acacia* species, allowed mapping the potential spatial and temporal coincidences between cultural services and invasive alien plants in North of Portugal, under a climate change scenario.

Thus, in general, human activities and interactions with the three *Acacia* species occurred mainly in the coastal zone and central North of Portugal, and *A. dealbata* represented the species with the highest presence in cultural hotspots. Furthermore, areas of spatial coincidence between visitation and *A. dealbata* may increase in the future due to changes in environmental conditions, in contrast to areas of coincidence for *A. longifolia and A. melanoxylon*. Due to the limitations of our approach, it was not possible to assess whether the phenological characteristics of the species contributed to the attractiveness of the landscapes and, consequently, to their public appreciation and what other environmental and social contexts may be influencing the contributions of invasive species to the cultural services. However, we provide relevant insights for landscape and ecosystem planning for North of Portugal and demonstrate how cultural services mapping is essential to understand how societies interact with environmental change events, such as invasive plant species, currently and in the future.

Additionally, we hope to improve our methodology in future work and obtain more informative and inclusive conclusions regarding the dynamics between invasive species and cultural services. Thus, the approach presented here can be replicated for any area and for any species. This means that the resulting implications can be applied in the implementation of management plans for cultural services and biological invasions that are most appropriate for each country, thus contributing to achieving more realistic goals for nature conservation and the well-being of societies in a more sustainable way.

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