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Ecological optima show the potential diffusion of minor tree crops in *Xylella fastidiosa* subsp. *pauca*-infected areas through a GIS-based approach

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Site selection analysis is a fundamental methodology for the regeneration of *Xylella fastidiosa* subsp. *pauca* (*Xfp*) infected areas, with the introduction of *Xfp* immune/resistant tree crop species. The diffusion of these species could be assessed by combining ecological optima data, climate and soil attributes of the study area, and GIS tools. The study aimed to evaluate the potential suitability of eight *Xfp* immune tree crops, including Neglected and Underutilized Species (NUS) drought-resistant and new species, as follows: carob, hawthorn, prickly pear, mulberry, loquat, walnut, persimmon, and avocado. The use of GIS tools allowed the integration of different layers, such as climate and soil, to contribute to the identification of suitable areas for the cultivation of these tree crops helping the policy-makers to define plans for land use at a regional scale. Following the ecological optima, which represents the ideal environmental conditions for each species, this analysis provided valuable insights into the compatibility of the selected tree crops with the prevailing environmental factors in the affected area. Carob revealed its remarkable adaptability and drought resistance, presenting the broadest suitability. Hawthorn and Loquat also exhibited high adaptability, indicating their potential contribution to agricultural diversification and ecological balance. Conversely, crops like Avocado, Prickly pear, and Walnut, despite their economic value, demonstrated limited adaptability due to their specific soil and climate requirements. These findings can potentially contribute to the development of strategies for the policy-makers, aimed at diversifying and enhancing the resilience of agricultural systems, facing the problem of emerging quarantine pathogens and the incoming climate change, and highlighting the possibility of opening new cultivation scenarios in the zones affected by *Xfp*.

KEYWORDS

NUS crops, drought tolerance, land suitability, site selection analysis, decision-making

1 Introduction

The recent incursion and widespread devastation caused by *Xylella fastidiosa* subsp. *pauca* (*Xfp*) in the Apulia-South of Italy has significantly impacted the regional olive cultivation and, by extension, its economy and cultural heritage (Calabrese et al., 2012; Scortichini, 2020). Olive trees, the cornerstone of Apulian agriculture, have not only economic but also historical and environmental significance, forming an integral part of the Mediterranean landscape and biodiversity (White et al., 2017; Garofalo et al., 2024a), leading it to be the region with major production of olive oil (Ciervo and Scortichini, 2024). However, the spread of *Xfp* has led to the death of millions of olive trees across Apulia, necessitating urgent research into new cropping systems, sustainable agricultural alternatives, and land management strategies to mitigate this crisis (Saponari et al., 2019; Maldera et al., 2023). Recent studies have emphasized the importance of exploring alternative crops that could be cultivated in the affected areas as a viable solution to the socio-economic and environmental challenges posed by the *Xfp* outbreak (Alhajj Ali et al., 2023).

1.1 Minor tree crops

Neglected and Underutilized Species (NUS) are crucial for their multifaceted benefits, particularly in enhancing biodiversity, contributing to food security, and mitigating climate change impacts. Among the wide range of species, two of relevant interest for *Xfp*-infected areas could be Carob and Hawthorn[1]. Carob (*Ceratonia siliqua* L., 1753) thrives in semi-arid conditions, making it a valuable species for arid and poor soils where other crops might fail (Batlle and Tous, 1997). Carob tree drought resistance and low water requirement position it as a critical species for adaptation strategies in increasingly arid environments (Correia et al., 2010; Eshghi et al., 2018), being able to mitigate the stress caused by soil flooding through adaptive mechanisms (Garofalo et. al, 2024b). Carob pods are a rich source of sugars, proteins, and essential nutrients, offering a gluten-free alternative to cocoa that can be used in a variety of food products, hence addressing food security and providing income generation opportunities for rural communities (El Batal et al., 2016). Hawthorn (*Crataegus azarolus* L., 1753) presents unique advantages: agronomically, this species is valued for its hardiness and ease of cultivation, thriving in a wide range of soils and conditions. Hawthorns are particularly noted for their beneficial effects in conserving biodiversity, serving as host plants for various insect species, and providing food and shelter for wildlife. Food-wise, the fruits of Hawthorn are highly nutritious, and rich in antioxidants, vitamins, and minerals, with traditional uses ranging from jams and jellies to medicinal products that have been linked to cardiovascular benefits (Zhang et al., 2001). The walnut tree (*Juglans regia* L., 1753) serves as a multifaceted asset in sustainable agriculture and ecological balance. Walnuts are highly valued for their adaptability and economic contribution, particularly in temperate climates where they thrive. Their deep root systems enhance soil structure and fertility, making them vital in agroforestry systems for intercropping and improving land use efficiency (McGranahan and Leslie, 2012). Moreover, the cultivation of walnuts contributes to carbon sequestration, a critical factor in mitigating climate change. These trees capture atmospheric carbon dioxide, storing carbon in their biomass and soil, thus contributing to the reduction of greenhouse gases (GHGs) (Vinceti et al., 2013). Moreover, walnuts offer significant nutritional benefits, thus they are rich sources of essential fatty acids, proteins, vitamins, and minerals, playing a crucial role in human diets and health (Ros, 2010). The global demand for walnuts has been rising, not only for direct consumption but also for their use in various food products, highlighting their importance in food systems and economies (Martínez et al., 2010). The White Mulberry (*Morus alba* L., 1753) is highly appreciated for its adaptability to various soil types and environmental conditions (Ercisli and Orhan, 2007). Its leaves serve as the primary food source for the silkworm (*Bombyx mori*), which is central to the silk industry, thus supporting the livelihoods of millions of people worldwide (Butt et al., 2008). Furthermore, the fruits of Morus alba are rich in vitamins, minerals, and antioxidants, offering health benefits and nutritional value to diets (Ercisli and Orhan, 2007). Prickly pear (*Opuntia ficus-indica* (L.) Mill., 1768) is exceptionally resilient to harsh environmental conditions, due to its cacti, address them to sustainable agriculture in drought-prone areas and contributing to food security and rural livelihoods by providing fruits, fodder, and even natural fencing (Choukr-Allah et al., 2016). Their minimal water requirements align with sustainable water management practices, essential in combating water scarcity. The nutritional value of prickly pear is significant: the fruits are rich in vitamins, minerals, and antioxidants, offering health benefits such as blood glucose regulation, which is crucial in diabetes management (Feugang et al., 2006). The persimmon (*Diospyros kaki* L.f., 1782) is a fruit tree of significant relevance, offering multiple benefits from agronomic, and food perspectives. Persimmons are rich in vitamins A and C, minerals, and dietary fibers, contributing to diversified and healthy diets (Castillo et al., 2023). The Loquat (*Eriobotrya japonica (Thunb.) Lindl., 1821*) is praised for its hardiness and low maintenance requirements. Its resilience to pests and diseases contributes to sustainable agricultural practices by reducing the need for chemical inputs (Lin et al., 2019). The tree exhibits remarkable adaptability to environmental stresses, including drought and temperature fluctuations, making it a strategic crop for regions facing climate variability (Demir, 1987; Freihat et al., 2008). The tree's evergreen nature and dense foliage offer an effective contribution to carbon sequestration and mitigation of climate change. The fruits are rich in vitamins (notably vitamins A and C), minerals, antioxidants, and dietary fiber, supporting a balanced diet and contributing to human health (Khouya et al., 2022). The Avocado (*Persea americana* Mill., 1768) stands as a crucial agricultural commodity, not only for its nutritional value but also for its economic implications. Originating from south-central Mexico, the avocado tree has transcended its native boundaries to become a globally new tropical fruit into different diets and cultures. The cultivation of avocados is both a challenge and an opportunity: avocado trees are highly demanding in terms of climatic and soil conditions, preferring well-drained soils and a climate without

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[1] http://www.nuscommunity.org/nus/neglected-underutilized-species/species-list/.

extreme temperatures. However, when these conditions are met, they can be highly productive for decades, offering substantial economic benefits to growers. Innovations in irrigation, pest management, and breeding have improved yields and resilience, making avocado farming more sustainable and efficient (Sommaruga and Eldridge, 2021). Additionally, avocados contribute to biodiversity, as their cultivation supports a range of organisms, including pollinators crucial for the trees' flowering and fruit set. Rich in healthy fats, vitamins, and minerals, avocados contribute to a balanced diet, supporting heart health and offering anti-inflammatory properties (Dreher and Davenport, 2013). The demand has also raised concerns about sustainability, water use, viability under water scarcity and salinity conditions, and the social impacts of intensive cultivation (Ramírez-Mejía et al., 2022). These species offer not only economic resilience but also potential benefits to the region's biodiversity and ecological balance, contributing to the sustainable development of agricultural systems in the wake of *Xfp* impact.

1.2 GIS applications in site selection analysis and aim of the work

Choosing the right location for an industrial tree plantation is essential. This decision should be based on sustainable exploitation of the soil's productivity and the suitability of local climate conditions to ensure the best possible growth of the selected tree species (Muñoz-Flores et al., 2011). Geographic Information Systems (GIS), as noted by Zhu, 2016, are crucial in advancing planning and land management strategies, facilitating the collection, organization, analysis, and visualization of spatial data. Pan and Pan (2012) emphasize the essential goal of land suitability assessments in agriculture to evaluate the capabilities and limitations of land for crop cultivation. In modern agricultural practices, land management, GIS plays a key role (Bill et al., 2012; Shadeed et al., 2017); this approach includes evaluating land suitability for crops using Boolean mapping techniques, as well as leveraging remote sensing (RS) imagery to enhance the accuracy and efficiency of these assessments (Hoobler et al., 2003; Wahba et al., 2007; Lanya and Manalu, 2021). Furthermore, concerning agroecological zoning, the integration of satellite remote sensing allows for a comprehensive analysis that considers topographical, vegetation, climate, and soil data (Akpoti et al., 2019). This multidimensional approach to land site selection analysis ensures that agricultural land use is optimized, promoting sustainable and productive farming practices.

Given the urgent need for sustainable agricultural alternatives in Apulia, this paper aims to evaluate the potential ecological suitability of eight different tree crops, including NUS, drought resistant, and new species, in the Apulian areas infected by *Xfp*. Utilizing GIS-based site selection analysis, this study seeks to provide comprehensive insights into the feasibility and potential impacts of introducing these alternative crops, thereby contributing to the diversification and resilience of the Apulian agricultural landscape in the face of ongoing and future Phyto pathological challenges. This approach provides valuable insights into the compatibility of these species with the environmental conditions in *Xfp*-affected areas, offering innovative strategies for agricultural diversification, and opening new cultivation scenarios.

2 Materials and methods

2.1 Study area

The Apulia region, South of Italy (Figure 1A), serves as a vital agricultural hub renowned for its extensive olive groves. These groves contribute significantly to the local economy through olive oil production and play a crucial role in biodiversity conservation and landscape heritage. In this study, we focused on the areas where *Xfp* is present and is constantly monitored [16.922 E, 39.789 N; 18.520 E,

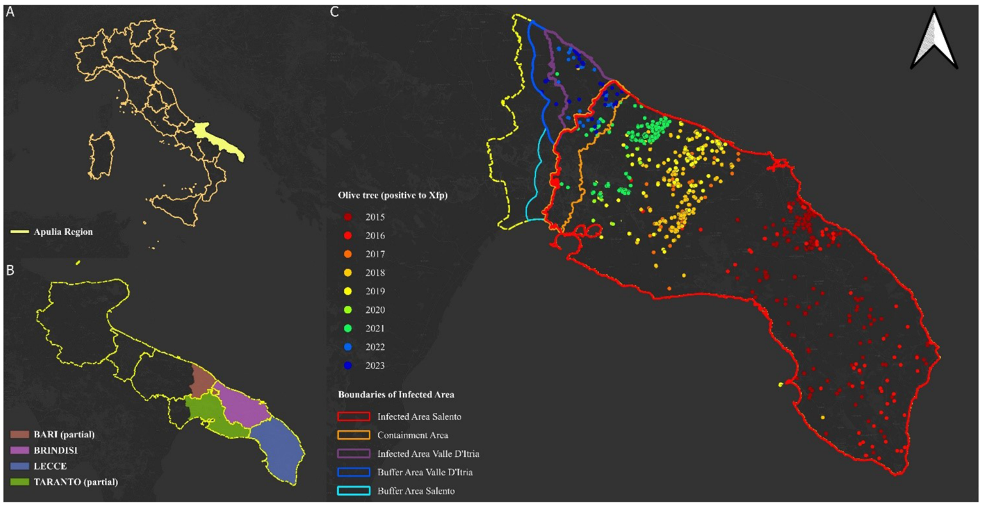

FIGURE 1
(A) Apulia region at national scale; **(B)** location of the four infected provinces (Bari and Taranto are partial); and **(C)** distribution of olive orchards tested positive to *Xfp* and boundaries of infected area. For each area different restriction measures are applied (OpenStreetMap Contributors, 2024).

41.082 N] (Figure 1B); The administrative limitations, in terms of the single province and region at national scale, were defined using the shapefiles of the Regional Territorial Landscape Plan – PPTR (updated on 15 November 2021) and Italian National Statistics Institute (updated on 2023), respectively. Additionally, the boundaries of the infected area (infected, containment, and buffer zone) were demarked using the regional Web Map Service (WMS) (emergenzaxylella.it, 2024a); the points show the distribution of infected olive trees considering a period from 2015 to 2023 (Figure 1C). These data were retrieved until 2021 using the online available dataset (Raparelli and Bajocco, 2023). Furthermore, to include 2022 and 2023 data in the analyses, we digitalized the data of the official regional monitoring authority by downloading each report from the *Xylella* emergency official site (emergenzaxylella.it, 2024b). These data confirm the capability of the vector *P. spumarius* to widespread OQDS against olive orchards (Figure 1C; EFSA, 2015).

2.2 Climate dataset

Thermo-pluviometric data (with hourly frequency) considering a long-term period (1994–2023), have been provided by Regional Agency for Irrigation and Forestry Activities (ARIF). For the investigated zone, we considered 44 agro-climatic stations (Figure 2A) to process, compute, and interpolate the key climate variables for site selection analysis as rainfall (mm) and temperature (° C) threshold. In particular, Chilling Hours (CH) and Growing Degree Days (GDD) have been obtained using *fruitclimpad* and *ChillR* package (R software CRAN), respectively (Luedeling and Brown, 2011; Luedeling et al., 2011; Luedeling, 2012a, 2012b; Miranda et al., 2021). Inverse Distance Weighting (IDW) interpolation, a widely used deterministic method for spatial interpolation, was employed to illustrate the spatial variability of climatic patterns across the study area, emphasizing the significance of understanding climatic gradients in determining areas suitable and non-suitable from a climatic perspective (Supplementary Figure S1). IDW interpolation operates on the principle that points closer to the prediction location have a greater influence on the predicted value than points further away, with the degree of influence determined by the power parameter, *p*. Fine-tuning of this *p* parameter through Leave-One-Out Cross Validation (LOOCV) ensures the optimal balance between local detail and overall trend, enhancing the accuracy of spatial predictions (Figure 2B). This methodology is particularly pertinent in the context of the middle-south and south of the Apulia region, where climatic variability – characterized by gradients in temperature, precipitation, and other climatic factors – plays a crucial role in delineating areas conducive to specific agricultural practices, conservation efforts, and urban planning. By employing IDW interpolation fine-tuned with LOOCV, this study provides a nuanced understanding of the region's climatic diversity, facilitating informed decision-making for land use and resource management based on climatic suitability. Lu and Wong's exploration of the effectiveness of LOOCV in IDW interpolation (Lu and Wong, 2008) offers a methodological framework for optimizing the *p* parameter, ensuring the precision of spatial predictions. Voronoi polygons were employed for variables counting the days when temperatures exceeded specific thresholds (Supplementary Figure S1). This approach, which divides a plane into regions based on distances to a specific set of points, ensures that each location within a given Voronoi polygon is closer to its generating point than to any other, allowing for an accurate representation of temperature

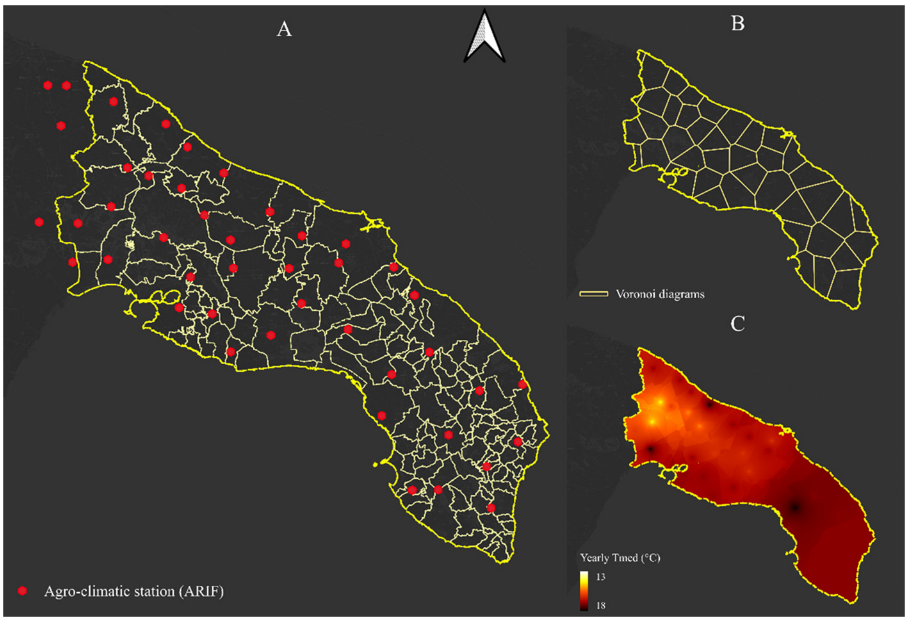

FIGURE 2
(A) The positions of agro-climatic stations, managed by Region al Agency for Irrigation and Forestry Activities (Regional Agrometeorological service – ARIF Puglia), used for gathering climate data. **(B)** Maps show the Voronoi diagrams, and the spatial variability of key climate variables obtained with IDW interpolation. (OpenStreetMap Contributors, 2024). **(C)** Map shows the distribution of yearly average temperature in the selected area.

distribution across the study area. The use of Voronoi diagrams for spatial analysis in climatology, as demonstrated by Sugihara and May (1990), provides a robust framework for mapping and analyzing temperature exceedances over thresholds. This methodology is particularly relevant in regions with significant climatic gradients, such as the Apulia region, where the spatial distribution of temperature-related variables can significantly influence agricultural practices and biodiversity conservation (Figure 2B).

2.3 Soil dataset

The regional soil database was sourced from the ACLA 2 project (ACLA 2; Agroecological characterization of the Apulia region as a function of production potential; Steduto and Todorovic, 2001) is dedicated to mapping the agroecological features of the Apulia region with an emphasis on its agricultural productivity potential (Figure 3). This comprehensive project facilitated the extraction of critical soil data, which included information on soil pH, texture (following the USDA classification guidelines), and salinity levels (ECe, dS/m), all of which were meticulously compiled into shapefiles for detailed analysis (Alhajj Ali et al., 2023). These data layers are instrumental in understanding the soil's suitability for various types of crops. The maps provide a visual representation of these essential soil parameters, showcasing maps that detail the distribution of soil pH, salinity, and texture throughout the surveyed regions. This graphical illustration aids in the immediate identification of areas with optimal or challenging conditions for agricultural practices, serving as a valuable resource for researchers and practitioners alike in making informed decisions regarding land use and crop management.

2.4 Alternative tree crops and ecological optima

The site selection analysis focused on the suitability of different tree crop species, like NUS (carob and hawthorn), drought-resistant (prickly pear), and high-water requirements species, such as mulberry, loquat, persimmon, and avocado. These species were considered because they are not included in the list, due to their resistance to *Xfp* (emergenzaxylella.it, 2024c). Ecological optima for each species were found through extensive bibliographic research, focusing on climate and soil conditions for these tree crops (Table 1). Values may also vary among cultivars because the response to these optima is strongly cultivar-dependent (Wang et al., 1992): the ones better adapted to high and low temperatures evolve their root structures to enhance water and nutrient uptake efficiency, aiming to maintain stable yields in these challenging conditions (Calleja-Cabrera et al., 2020). Furthermore, the suitability of this species in a specific region can vary continuously also based on what new species and cultivars breeders propose each year to the farmers (Kopeć, 2024).

Rainfall (mm/year) and chilling hours (hours) further contribute to defining the ecological optima for these tree crops, with specific requirements that ensure successful cultivation and yield. The gathered bibliographic data underscore the complex interplay between climate and soil conditions in cultivating these tree crops, highlighting the necessity of targeted research and management strategies to optimize growth conditions across the different regional areas.

2.5 Site selection analysis

The application of GIS and programming language software (R software 4.3.3 version) in site selection analysis enabled the creation of overlay raster and distribution maps of suitability area. Leisz et al., 2005 highlighted the effectiveness of GIS-based approaches in evaluating land suitability. The LTR (Long Term Release) version of *QGIS* software (*3.34.4*), employing the *WGS 1984 UTM/ZONE 33N* (*EPGS: 32633*) coordinate reference system, was used for cartographic and geospatial analyses. The process involved integrating various parameters to produce a comprehensive suitability map. For each ecological optima considered in site selection analysis for different crops, binary raster layers were created. In these sets, the raster layers pixel has been marked as 0.0 to indicate a no-suitable zone and 1.0 to indicate a suitable area, leading to the creation of the final suitability map that identified

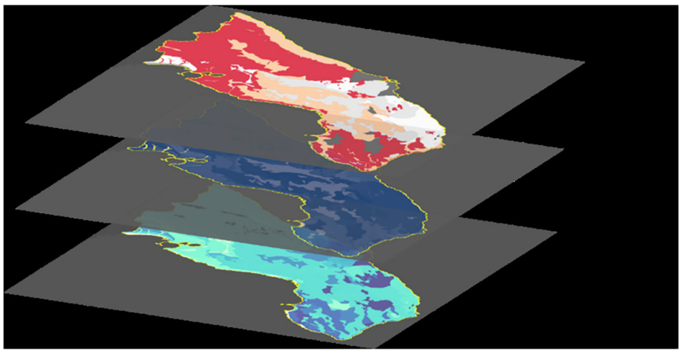

FIGURE 3
Maps displaying key soil characteristics such as texture, salinity (ECe, dS/m), and pH across the studied areas in investigated zone, utilizing the ACLA2 database.

TABLE 1 Ecological optima extracted from bibliographic research for the selected fruit tree crops.

Tree Crop Species	Soil threshold		Temperature threshold			Tmed	Rainfall	ChillH	GDD	References
	pH	Ec	Texture	Tmin$_1$	Tmax$_2$					
Avocado (***Persea americana* Mill.**)	5.0–7.0	<2 dS/m	sand, sandy-loam, clay-loam	count when temperature <= −5°C from more than 4 h in whole year		10–35 °C – from February to May	530–650 mm from April to October	NA	>= 2200 heat unit (growth cycle)	Bayram and Arslan, 2007; Bayram, 2010; Bender et al., 2012; Bayram et al., 2014 (twice); Pillsbury and Huberty, 1944; Du Plessis and Koen, 1987; Lomas, 1988; Lovatt, 1990; Dorantes et al., 2004; Mickelbart et al., 2007; Crowley, 2008; Ministry of Agriculture of Greece, 2019; Nektarios et al., 2021; Salazar-Garcia et al., 2005; Whiley and Winston, 1987; Steinhardt, 1991; Salgado and Cautín, 2008; Tamam, 2008; Wolstenholme, 2013; Selim et al., 2018; NASS, 2020
Carob (***Ceratonia siliqua* L.**)	6.2–8.6	<6.8 dS/m	all except waterlogging	count when temperature < −4°C during the winter	count when >= 40°C during the summer	NA	250–500 mm/year	NA	NA	Batlle and Tous, 1997; Correia et al., 2010; El Kahkahi et al., 2016; Santos et al., 2019
Hawthorn (***Crataegus azarolus* L.**)	6.9–7.7	1.88–4.6 dS/m	NA	NA	NA	11–17°C (year)	920–1030 mm/year	NA	NA	Radha and Khwarahm, 2022; Data not shown
Loquat (***Eriobotrya japonica* Lindl.**)	5.0–8.0	<4 dS/m	Sand loams or clay loams	count when temperature < −3°C	max mean T summer > 35°C	NA	1000–1200 mm/year	100–200	NA	Wu and Dodge, 2005; Polat, 2007
Mulberry (***Morus alba* L.**)	6.5–7.5	<1.0 dS/m	clay loamy soils	count when temperature < −30°C	count when > =#146;40°C during the summer	NA	600–2500 mm/year	400	NA	Jones and Costello, 2007; Rohela et al., 2020
Persimmon (***Diospyros kaki* L.f.**)	5.5–6.5	<1.2 dS/m	clay-loam, clay and loamy	count when temperature < −13/−16°C	NA	20–25°C during fruit growth	700–900 mm/year	> 200	NA	Chujo et al., 1973; Ercisli et al., 2008; Buesa et al., 2013; Giordani et al., 2015; Perucho, 2015; Visconti et al., 2017; Intrigliolo et al., 2018; Jain et al., 2023
Prickly pear (***Opuntia ficus-indica* ((L.) Mill.**)	5.1–8.1	<2 dS/m	no silty and loamy	min mean T winter >5°C	NA	18–23°C (year)	350–500 mm/year	NA	NA	Le Houérou, 1992; Bakewell-Stone, 2012; Inglese et al., 2017; Prisa, 2021;
Walnut (***Juglans regia* L.**)	6.5–7.0	<1.7 dS/m	loam, silty loam, silty clay loam, silty, clay loam, sandy loam	count when temperature < −2°C (from half of march to half of may)	count when >40° C during summer	NA	650–700 mm/year	650	NA	Amzăr, 1974; Akça, 2000; Aslamarz et al., 2009; Cociu, 1972; Cisneros et al., 2009 (twice); Cosmulescu et al., 2010 (twice); Ponder, 2004; Payghamzadeh and Kazemitabar, 2011 (twice); Ramos, 1997 (twice); Prevenda, 2020; Solar, 1989; Wilkinson, 2005; Scedei et al., 2020; Yilmaz, 2021

1,2: Tmin and Tmax refers to a count when a minimum and maximum temperature threshold was exceeded.
NA, not applicable.

areas meeting all specified ecological criteria. Once individual raster layers were prepared, they were merged with a shapefile of agricultural zones identified by Corine Land Cover (CLC18v.20). This method, which is straightforward yet effective, is a commonly employed algorithm in GIS spatial analysis and has been utilized in prior studies (Alhajj Ali et al., 2023). It is of notable attention for the resulting suitable map for hawthorn, loquat, and avocado where rainfall (mm/year) optima have not been considered because they exceeded the regional average rainfall (mm/year). The reason why they were still considered is because of the use of irrigation for these orchards.

3 Results

The *Xfp*-resistant tree species responded significantly to the different pedo-climatic conditions. In Table 2 the growing areas suitable for each tree crop in the *Xfp* infected areas are reported. This detailed analysis encapsulated the potential diffusion of these minor tree species.

The results revealed nuanced insights into the matching of the ecological optima for each crop species with the pedological and climatic conditions of the assessed areas. The aggregated data, culminating in the total suitable area for each crop species, showed a comprehensive overview of the agricultural potential and regional suitability landscapes for these tree crops. This information is invaluable for stakeholders in agriculture, including farmers, policy-makers, and researchers, as it guides strategic planning, resource allocation, and the development of sustainable farming practices.

A map for each species was made, highlighting which zones are the most suitable (Figures 4, 5). This distribution highlighted the species-specific considerations required when planning for agricultural diversification and the relevance of aligning crop ecological requirements with the pedoclimatic characteristics of each area.

TABLE 2 Suitable areas (ha) of the selected fruit tree crops *Xfp*-infected areas: Bari (BA), Brindisi (BR), Lecce (LE) and Taranto (TA).

TREE CROPS	SUITABLE AREA (ha)				TOTAL
	BA*	BR	TA*	LE	
AVOCADO	0	22652	5940	34528	63120
CAROB	13577	84005	39813	125968	263362
HAWTHORN	13813	64391	35405	59570	173179
LOQUAT	13166	68628	30688	140462	252943
MULBERRY	0	15792	774	14913	31479
PERSIMMON	0	0	0	13114	13114
PRICKLY PEAR	0	1557	949	85229	87734
WALNUT	0	416	0	8260	8677
AGRICULTURAL ZONES	49356	149060	85284	203683	487383

*the area evaluated referred to a partial zone of the province.
Agricultural zones were identified by using Corine Land Cover (CLC18v.20).

On a total of 487,383 ha available in agricultural zones evaluated, avocado showed notable suitable areas in the province of BR (22,652 ha) and LE (34,528 ha), indicating that those areas could provide favorable climatic and soil conditions (Figure 4). However, in BA avocado cultivation was not suitable. Carob showed the highest number of hectares available for cultivation (263,362 ha), with almost half of them localized in Lecce (125,968 ha). Hawthorn exhibited widespread suitability, with significant areas in all provinces, particularly in BR (64,391 ha) and LE (59,570 ha). Loquat exhibited a widespread suitability across all surveyed provinces, with a significant presence especially in LE (140,462 ha), followed by BR (68,628 ha), TA (30,688 ha), and BA (13,166 ha). The total suitable area for loquat cultivation amounted to 252,943 hectares (Table 2; Figure 4). Mulberry, although showing a more limited distribution of suitability, with a notable absence of data for BA and a relatively small suitable area in TA (774 ha), identified pockets of high suitability in BR (15,792 ha) and LE (14,913 ha) (Figure 5). Persimmon showed a focused area of suitability exclusively in the province of LE, with a total of 13,114 hectares (Figure 5). Walnut presented a rather limited distribution, with a notable suitability only in LE (8,260 ha) and a minimal area in BR (416 ha), totaling 8,677 hectares. Prickly pear has identified suitable areas primarily in LE (85,229 ha), with smaller areas in BR (1,557 ha) and TA (949 ha), leading to a total of 87,734 hectares.

A focus was made only in olive tree zones (Supplementary Table S1) with a total area of 240,335 ha. Olive tree emerges as the most extensive crop in terms of suitability and area coverage (240,335 on a total of 487,383 ha) (Grotti et al., 2019). Such extensive cultivation is reflective of the olive's historical, cultural, and economic significance, especially in the production of olive oil. Still, the Carob tree, with a total suitability of 127,468 ha, predominantly in the BR and LE provinces, highlights the great suitability of this crop. Similarly, the loquat, covering 116,885 ha with a significant presence in the LE province, illustrates the market's demand for its fruits, fostering its cultivation in subtropical climates. The data also reveals the cultivation of hawthorn and mulberry, with 75,047 and 14,648 ha respectively, pointing towards their specific use. Emerging crops like the avocado and persimmon, with 23,885 ha and 8,156 ha respectively, signify diversification in agricultural practices. Their cultivation, although limited compared to traditional crops, points to a trend towards the integration of more diverse and high-value crops into the agricultural landscape. The analysis of prickly pear and walnut, with their distinct ecological niches, underscores the importance of understanding and leveraging environmental conditions for agriculture. Prickly pear's adaptation to arid conditions, especially in the LE province, and walnut's specific requirements reveal the potential for niche markets and the importance of biodiversity in agriculture.

4 Discussion

The potential diffusion results of the examined minor fruit tree species, shown in Table 2 and in Figures 4 and 5, were strictly

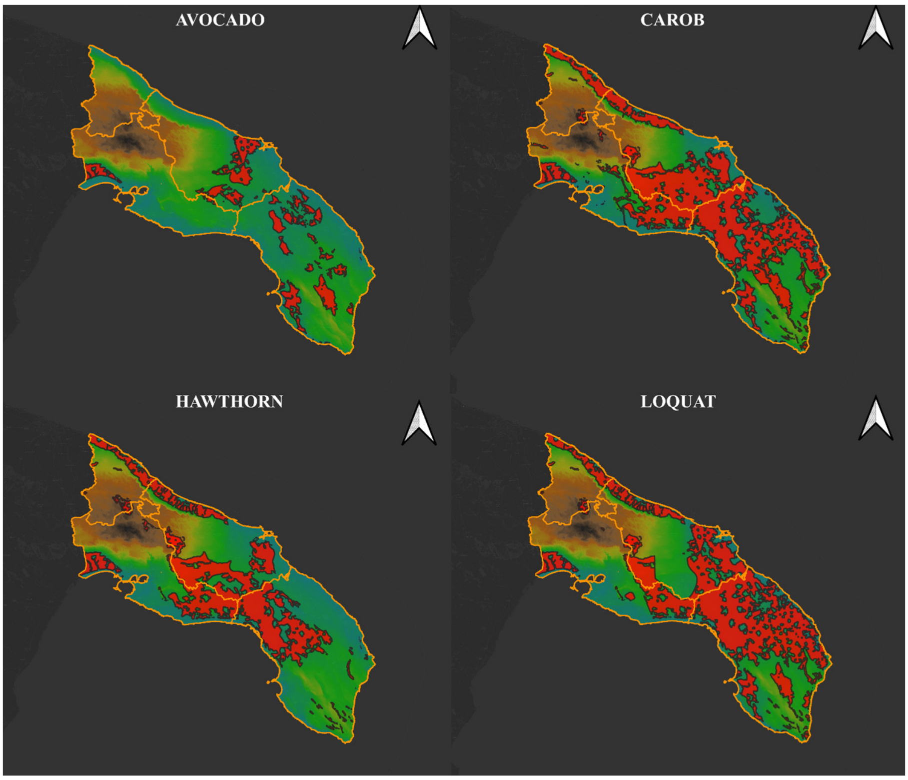

FIGURE 4
Distribution maps of the suitable areas for avocado, carob, hawthorn, and loquat within the agricultural zones affected by *Xfp* obtained. The different colored zones highlight areas that are suitable for each species, based on a combination of the different ecological optimal considered (binary site selection analysis).

related to the essential ecological parameters for optimal growth, reported in Table 1. However, it's fundamental to understand which ecological parameters played a key role in assessing the suitable areas for each species.

The avocado trees have a broad soil pH tolerance, ranging from 5.0 to 7.0, which allows them to thrive in slightly acidic to neutral soil environments. For this, it can be grown in diverse soil conditions, with a preference for well-drained soils to avoid issues like root rot (Salgado and Cautín, 2008). The salinity tolerance is less than 2 dS/m, indicating sensitivity to high soil salinity levels; thus, they are best suited to areas with low to moderate salinity in irrigation water or soil, like the zone in the north of Brindisi or the south of Lecce ((Nektarios et al., 2021). Temperature requirements are notably specific: they cannot withstand temperatures that fall to −5°C or lower for more than 4 hours in the entire year, highlighting their vulnerability to frost. The median temperature suitable range isn't explicitly provided, but given their sensitivity to cold, avocados thrive in regions with mild, frost-free winters (Lomas, 1988; Bayram et al., 2014). Rainfall requirements range from 530 to 650 mm from April to October, suggesting a preference for a moderate amount of water distributed throughout the growing season (Nektarios et al., 2021). Considering the avocado rainfall threshold, all the water requirements not satisfied by rainfall will be reached using irrigation. Avocados have a Growing Degree Day (GDD) requirement of over 2200 GDD (Wolstenholme, 2013). This high requirement limited the suitability, excluding all the northern parts of Salento and a consistent part of the Adriatic coast. Finally, the specific requirements for temperature and water make them less adaptable than other species, particularly regarding cold tolerance and soil salinity (Supplementary Figures S1, S2). Only 13% of the total agricultural zones can be planted as avocados, with more than 50'000 hectares in the provinces of Brindisi and Lecce (Table 2).

The carob trees showed an environmental condition that supports the cultivation of this drought-resistant and economically valuable crop (Figure 4). In terms of soil pH, it can adapt in a range from 6.2 to 8.6 and can withstand higher salinity levels up to 6.8 dS/m (Correia et al., 2010). This adaptability suggested that carob trees could be cultivated across a wide range of soil types, except in waterlogged conditions and very high pH soils like in Torchiarolo and Carovigno. Temperature thresholds indicated a tolerance for temperatures below −4°C during the winter and a requirement for temperatures equal to or above 40°C during the summer (Batlle and Tous, 1997). The average rainfall ranged between 250 and 500 mm/year, making all the area suited. Chilling hours and GDD are still not known for this species, so no information could be given (Santos et al., 2019). The major part of the excluded areas for Carob is related to clay soils, not suited for almost every fruit tree species. With this data, the Carob tree demonstrated the broadest adaptability in the selected zone, with more than 260'000 hectares vocated to its cultivation (Supplementary Figures S1, S2).

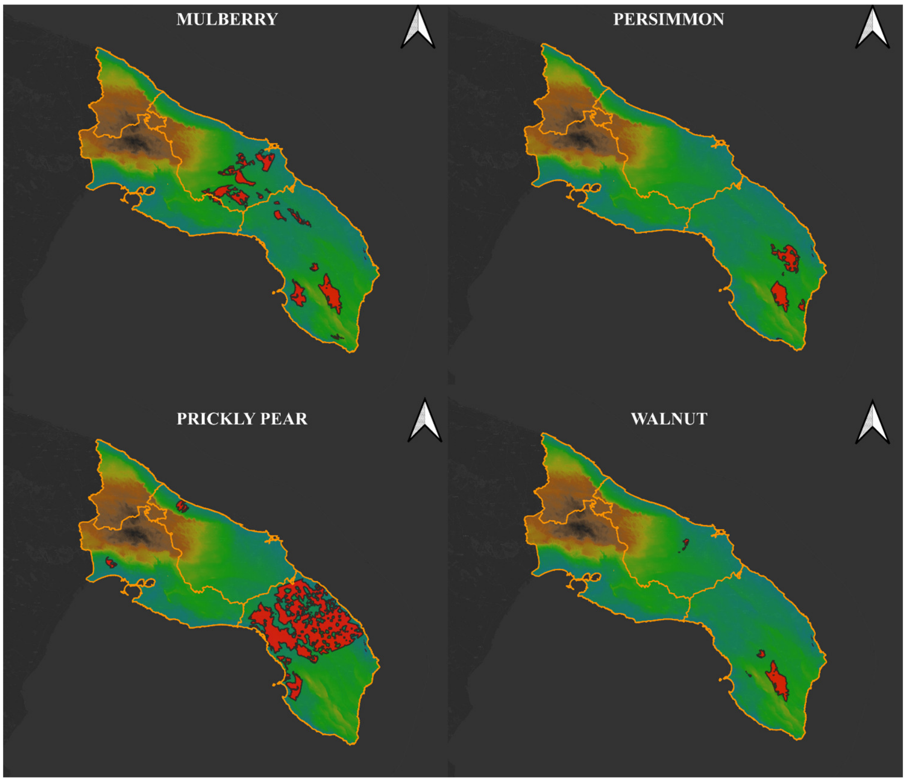

FIGURE 5
Distribution maps of the suitable areas for mulberry, persimmon, prickly pear, and walnut within the agricultural zones affected by *Xfp* obtained. The different colored zones highlight areas that are suitable for each species, based on a combination of the different ecological optimal considered (binary site selection analysis).

The hawthorn tree is the third most suitable species, with 36% of the total agricultural zone that could be dedicated to this crop (Supplementary Figures S2, S3). While there wasn't a specific texture preference, it indicated a pH range of 6.9–7.7 and salinity tolerance between 1.88 to 4.6 dS/m (Radha and Khwarahm, 2022). Although temperature preferences were not detailed, the specified average temperature range of 11 to 17°C and rainfall requirements of 920–1030 mm annually underscored Hawthorn's preference for temperate climates with adequate precipitation (Radha and Khwaramh, data not published). Considering the very few numbers of published information about this crop, the average temperature played a relevant role in land suitability. However, Hawthorn reflected its adaptability and the broad ecological niches it could occupy (Figure 4).

The loquats demonstrated the second higher adaptability, with more than 50% of suitable zones. In terms of soil pH, this crop tolerates a range from 5.0 to 8.0(Table 2). They can withstand salinity levels up to 4 dS/m, indicating a moderate tolerance to saline conditions (Wu and Dodge, 2005). Temperature requirements suggest loquats cannot endure temperatures below -3°C, while the optimal maximum mean summer temperature is above 35°C (Polat, 2007). In the center of the Salento (a relevant Voronoi polygon caused the subtraction of all the orchards in that zone due to very low temperatures in some days of the winter (Supplementary Figure S3). Moreover, they need a rainfall range of 1000–1200 mm/year and 100–200 chill hours, positioning them as suitable for a variety of temperate to subtropical environments (Polat, 2007). The high water demand made the use of irrigation to fill the gap between rainfall and water necessary (Supplementary Figures S2, S3).

The mulberry was identified to prefer clay loamy soils, with a pH range of 6.5 to 7.5 and a low salinity tolerance of below 1.0 dS/m, indicating the need for soils with good moisture retention and low salt content (Jones and Costello, 2007). These thresholds were very strict for the study area, leading to a suitability of only 31,500 hectares (Figure 5). Temperature thresholds highlighted robustness against low winter temperatures (no lower than −30°C) and a requirement for summer temperatures to reach or exceed 40°C (Jones and Costello, 2007; Rohela et al., 2020) (Supplementary Figures S2, S3). Rainfall adaptability was broad, ranging from 600 to 2500 mm annually, with a chilling requirement of 400 hours, suggesting versatility in various humid climates (Rohela et al., 2020).

The persimmon tree indicated a very localized potential for persimmon cultivation, suggesting that the environmental conditions in LE are particularly conducive to this crop (Figure 5; Supplementary Figures S2, S3). This crop could fit in soils with pH levels ranging from 5.5 to 6.5, indicating a preference for slightly acidic to neutral soil conditions (Buesa et al., 2013). They are relatively sensitive to salinity, with a tolerance of less than 1.2 dS/m, suggesting they are less adaptable to saline conditions compared to species like carob (Visconti et al., 2017; Intrigliolo et al., 2018). Also here, the proposed thresholds lead to a very low number (13,000 ha) of suitable orchards, exclusively concentrated in the lower part of the Salento. Temperature-wise, persimmons could not withstand extreme cold, with tolerance to temperatures not falling below −13°C to −16°C (Chujo et al., 1973). They require a median temperature range of 20–25°C during fruit growth and adequate rainfall between 700–900 mm/year (Perucho, 2015). The chilling hours requirement was not limiting, with only over 200 hours.

Particular behavior was observed for prickly pears. Only a wide stripe in the northern part of Lecce province was found to be suitable (42%), while only 1% of hectares could be used in BR and TA (Table 2; Supplementary Figures S2, S3). The crop exhibited a wide soil pH tolerance from 5.1 to 8.1, making it the most tolerant to acid soils and one of the most adaptable to various soil conditions (Le Houérou, 1992; Prisa, 2021). They have a salinity tolerance of less than 2 dS/m, indicating they can handle slightly saline environments (Bakewell-Stone, 2012). With a minimum mean winter temperature requirement of above 5°C, prickly pears are adapted to warmer climates and cannot withstand cold winters. The most important and the most limiting threshold resulted in the annual mean temperatures, which needed to be 18–23°C (Prisa, 2021). Furthermore, it required 350–500 mm of yearly rainfall, which positions them as well-suited to semi-arid to arid climates, given their lower water requirement compared to the other discussed species.

The scarcity of walnut suitable areas highlighted the selective nature of this tree species regarding climatic and soil requirements (Supplementary Figures S2, S3). Walnut trees were found to thrive in a few soil textures, with a pH preference ranging from 6.5 to 7.2 (Table 2) (Ponder, 2004). In particular, optimal soil conditions are identified in loams and silty compositions (Scedei et al., 2020). This parameter showed the highest relevance as a threshold, minimizing the suitable areas at a very low number of hectares, mostly in the lower part of Salento. Rainfall requirements were specified as 650–700 mm annually, with a chilling hour requirement of 650 (Cisneros et al., 2009; Prevenda, 2020; Yilmaz, 2021; Aslamarz et al., 2009). These two climatic parameters were the most relevant, compromising the suitability of a wide range of zones and excluding a relevant number of hectares, reducing at only the 2% of the agricultural zones.

5 Conclusion

The research addressed the lack of information on introducing *Xylella fastidiosa subsp. pauca* immune/resistant tree crop species in Apulia Region. A site selection analysis through a GIS-based approach was useful to investigate the potential suitability of minor fruit tree crops in the *Xylella fastidiosa subsp. pauca* infected-areas. The analysis revealed that Carob, with its remarkable adaptability and drought resistance, presented the broadest suitability, offering a viable alternative for sustainable agricultural development in the area where the problem is not only the bacterium but also the availability of water for agricultural uses. Hawthorn and Loquat also exhibited high adaptability, indicating their potential contribution to agricultural biodiversity and ecological balance. Conversely, Avocado, Prickly pear, and Walnut, despite their economic value, demonstrated limited adaptability due to specific soil and climatic requirements, underscoring the importance of matching crop selection to local environmental conditions. The adoption of alternative crops, that fit the ecological optima in the affected regions, stands as proof of the resilience and adaptability of agricultural systems dealing with pathogens and climate threats. These outcomes highlighted the significance of targeted research for management strategies essential for policy-makers, to optimize growth conditions, ensure the sustainable development of agricultural practices in regions affected by plant pathogens, open new cultivation scenarios, and give new hopes for the olive growers that had suffered the impact of this bacterium into their orchards.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

LC: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft. FM: Data curation, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. SG: Data curation, Investigation, Methodology, Visualization, Writing – review & editing. GV: Writing – review & editing. SC: Funding acquisition, Resources, Supervision, Validation, Writing – review & editing.

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the table with the suitable areas resulting by an intersection against our shapefiles and olive tree zones shapefile (OLIVEMAP project).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2024.1421627/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Voronoi polygons highlighted in yellow show the case when the Tmin and Tmax threshold counting has been over zero defining the exclusion of the corresponding zone.

SUPPLEMENTARY FIGURE 2
Inverse Distance Weight (IDW) interpolation map referring to climate parameters.

SUPPLEMENTARY FIGURE 3
ACLA2 map referring to soil parameters.

References

Akça, Y. (2000). *Meyve türlerinde kullanılan anaçlar* Vol. 46 (Istanbul, Turkey: Gaziosmanpaşa Üniversitesi, Ziraat Fakültesi Yayınları).

Akpoti, K., Kabo-bah, A. T., and Zwart, S. J. (2019). Agricultural land suitability analysis: State-of-the-art and outlooks for integration of climate change analysis. *Agric. Syst.* 173, 172–208. doi: 10.1016/j.agsy.2019.02.013

Alhajj Ali, S., Vivaldi, G. A., Garofalo, S. P., Costanza, L., and Camposeo, S. (2023). Land suitability analysis of six fruit tree species immune/resistant to *Xylella fastidiosa* as alternative crops in infected olive-growing areas. *Agronomy* 13, 547. doi: 10.3390/agronomy13020547

Amzăr, G. (1974). "Zonarea culturii nucului în funcţie de condiţiile ecologice din România," in *Revista de Horticultură şi Viticultură* (Ministerul Agriculturii Publisher, Bucharest, Romania), 1974–1912.

Aslamarz, A. A., Vahdati, K., Rahemi, M., and Hassani, D. (2009). "Evaluation of chilling-heat requirements of some Persian walnut cultivars," in *VI International Walnut Symposium*, Melbourne, Australia. vol. 861. , 317–320.

Bakewell-Stone, P. (2012). Opuntia ficus-indica (prickly pear). *Forest.* doi: 10.1079/cabicompendium.37714

Batlle, I., and Tous, J. (1997). *Carob tree (Ceratonia Siliqua L.)* (Rome, Italy: IPGRI).

Bayram, S. (2010). *Annual Avocado Development Report (in Turkish).* Available online at: https://arastirma.tarim.gov.tr/batem/Belgeler/Kutuphane/Teknik%20Bilgiler/2010%20Aavokado%20gelisim.pdf (Accessed 22 April 2024).

Bayram, S., and Arslan, M. A. (2007). Effect of low and high temperature on avocado growing. *Horticultural Studies* 24, 9–19. Muratpaşa, Antalya, Turkey.

Bayram, S., Arslan, M. A., and Turgutoglu, E. (2014). Importance of avocado cultivation, cruising and proposed some varieties in Turkey. *Horticultural Studies* 23, 1–13.

Bender, G. S., Smothers, V. W., and Francis, L. (2012). "Site selection, road engineering and erosion control avocado production in California," in *Bender, G.S., (Ed.), A Cultural Handbook for Growers Second Edition Book One – Background Information* (California, United States of America: The University of California Cooperative Extension, San Diego County and The California Avocado Society). California: United States of America.

Bill, R., Nash, E., and Grenzdörffer, G. (2012). *GIS in Agriculture* (Heidelberg: Springer Berlin), 461–476. doi: 10.1007/978-3-540-72680-7

Buesa, I., Badal, E., Guerra, D., Ballester, C., Bonet, L., and Intrigliolo, D. S. (2013). Regulated deficit irrigation in persimmon trees (Diospyros kaki) cv.'Rojo Brillante'. *Scientia Hortic.* 159, 134–142. doi: 10.1016/j.scienta.2013.05.014

Butt, M. S., Nazir, A., Sultan, M. T., and Schroën, K. (2008). Morus alba L. nature's functional tonic. *Trends Food Sci. Technol.* 19, 505–512. doi: 10.1016/j.tifs.2008.06.002

Calabrese, G., Ladisa, G., and Pettiti, L. (2012). "Oliviculture and ancient olive orchards in the EU-Mediterranean area," in *A multi-scale and multi-level approach for conservation of ancient olive orchards in the Euro-Mediterranean region.* Eds. A. La Posta, C. Lacirignola and G. Mimiola (Apulia, Italy: IAMB, CIHEAM - Mediterranean Agronomic Institute of Bari), 2–23.

Calleja-Cabrera, J., Boter, M., Oñate-Sánchez, L., and Pernas, M. (2020). Root growth adaptation to limate change in crops. *Front. Plant Sci.* 11. doi: 10.3389/fpls.2020.00544

Castillo, M., Pons-Gómez, A., Albert-Sidro, C., Delpozo, B., and Besada, C. (2023). Acceptance, sensory characterization and consumption contexts for dehydrated persimmon slices, chips, leathers and powder: A consumer study. *Foods* 12(10), 1966. doi: 10.3390/foods12101966

Choukr-Allah, R., Rao, N. K., Hirich, A., Shahid, M., Alshankiti, A., Toderich, K., et al. (2016). Quinoa for marginal environments: toward future food and nutritional security in MENA and central Asia regions. *Front. Plant Sci.* 7. doi: 10.3389/fpls.2016.00346

Chujo, T., Hashimoto, T., and Ashizawa, M. (1973). The effect of temperature on the growth and quality of kaki fruit. II. Day and night temperature treatments during the stage of fruit enlargement. *Kagawa Daigaku Nogakubu Gakuzyutu Hokoku* 25, 25–34.

Ciervo, M., and Scortichini, M. (2024). A decade of monitoring surveys for Xylella fastidiosa subsp. pauca in olive groves in Apulia (Italy) reveals a low incidence of the bacterium in the demarcated areas. *J. Phytopathol.* 00, e13272. doi: 10.1111/jph.13272

Cisneros, O., Martínez, V., Montero, G., Alonso, R., Turrientes, A., Ligos, J., et al. (2009). Plantaciones de frondosas en Castilla y León. Cuaderno de campo. *Junta Castilla y León; FAFCYLE.* doi: 10.13140/RG.2.1.1880.9047

Cociu, V. (1972). *Aspecte Privind Tehnologia Culturii Nucului* (Bucharest, Romania: Agro Silvica de Stat), 124–133.

Correia, P. J., Gama, F., Pestana, M., and Martins-Loução, M. A. (2010). Tolerance of young carob (Ceratonia siliqua L.) trees to salinity. *Agric. Ecosyst. Environ.* 138, 253–259.

Cosmulescu, S., Baciu, A., Botu, M., and Achim, G. H. (2010). Environmental factors' influence on walnut flowering. *Acta Hortic.* 861, 83–88. doi: 10.17660/ActaHortic.2010.861.10

Crowley, D. (2008). Salinity management in avocado orchards. *California Avocado Society Yearbook* 91, 83–104.

Demir, S. (1987). Loquat growing. *Tarim Orman ve Kyisleri Bakanligi Narenciye Arastirma Enstitüsü Müdürlügü* 12, 30.

Dorantes, L., Parada, L., and Ortiz, A. (2004). *Avocado: post-harvest operation* (Rome, Italy: Food and Agriculture Organization of the United Nations), 67.

Dreher, M. L., and Davenport, A. J. (2013). Hass avocado composition and potential health effects. *Crit. Rev. Food Sci. Nutr.* 53, 738–750. doi: 10.1080/10408398.2011.556759

Du Plessis, S. F., and Koen, T. J. (1987). *Comparison of different calcium sources on avocado production* Vol. 10 (South African Avocado Growers' Association Yearbook), 49–51.

EFSA Panel on Plant Health (PLH) (2015). Scientific opinion on the risks to plant health posed by Xylella fastidiosa in the EU territory, with the identification and evaluation of risk reduction options. *EFSA J.* 13, 3989. doi: 10.2903/j.efsa.2015.3989

El Batal, H., Hasib, A., Ouatmane, A., Dehbi, F., Jaouad, A., and Boulli, A. (2016). Sugar composition and yield of syrup production from the pulp of Moroccan carob pods (Ceratonia siliqua L.). *Arabian J. Chem.* 9, S955–S959. doi: 10.1016/j.arabjc.2011.10.012

El Kahkahi, R., Moustaine, M., Mouhajir, A., Bachir, S., Lemrhari, A., Zouhair, R., et al. (2016). *Technical sheet on the culture carob tree (Ceratonia Siliqua L.) in Morocco*. Lyon, France: HAL science.

Emergenzaxylella.it (2024a). Available online at: https://www.sit.puglia.it/portal/portale_gestione_agricoltura/WMS (Accessed 3 April 2024).

Emergenzaxylella.it (2024b). Available online at: http://www.emergenzaxylella.it/portal/portale_gestione_agricoltura/Elenchi/risultati (Accessed 3 April 2024).

Emergenzaxylella.it (2024c). Available online at: http://www.emergenzaxylella.it/portal/portale_gestione_agricoltura/Documenti/Specie (Accessed 3 April 2024).

Ercisli, S., Akbulut, M., Ozdemir, O., Sengul, M., and Orhan, E. (2008). Phenolic and antioxidant diversity among persimmon (Diospyrus kaki L.) genotypes in Turkey. *Int. J. Food Sci. Nutr.* 59, 477–482. doi: 10.1080/09637480701538262

Ercisli, S., and Orhan, E. (2007). Chemical composition of white (Morus alba), red (Morus rubra) and black (Morus nigra) mulberry fruits. *Food Chem.* 103, 1380–1384. doi: 10.1016/j.foodchem.2006.10.054

Eshghi, S., Rostami, A. A., and Jamali, B. (2018). Carob tree: a suitable species for the future. *Acta Hortic.* 1190, 67–70. doi: 10.17660/ActaHortic.2018.1190.11

Feugang, J. M., Konarski, P., Zou, D., Stintzing, F. C., and Zou, C. (2006). Nutritional and medicinal use of Cactus pear (Opuntia spp.) cladodes and fruits. *Front. Biosci.* 11, 2574–2589. doi: 10.2741/1992

Freihat, N. M., Al-Ghzawi, A. A. M., Zaitoun, S., and Alqudah, A. (2008). Fruit set and quality of loquats (Eriobotrya japonica) as effected by pollinations under sub-humid Mediterranean. *Scientia Hortic.* 117, 58–62. doi: 10.1016/j.scienta.2008.03.012

Garofalo, S. P., Giannico, V., Costanza, L., Alhajj Ali, S., Camposeo, S., Lopriore, G., et al. (2024a). Prediction of stem water potential in olive orchards using high-resolution planet satellite images and machine learning techniques. *Agronomy* 14, 1–18. doi: 10.3390/agronomy14010001

Garofalo, S. P., Giannico, V., Lorente, B., García, A. J. G., Vivaldi, G. A., Thameur, A., et al. (2024b). Predicting carob tree physiological parameters under different irrigation systems using Random Forest and Planet satellite images. *Front. Plant Sci.* 15. doi: 10.3389/fpls.2024.1302435

Giordani, E., Picardi, E., and Radice, S. (2015). "El cultivo del caqui. Antecedentes e importancia económica," in *El Cultivo del Caqui*. Eds. M. L. Badenes, D. S. Intrigliolo, A. Salvador and A. Vicent (Generalitat Valenciana, Valencia, Spain), p.17–p.33.

Grotti, M., Puletti, N., Chianucci, F., Mattioli, W., Floris, A., Clementel, F., et al. (2019). "A plot sampling strategy for estimating the area of olive tree crops and olive tree abundance in a Mediterranean environment," in *Earth Observation Advancements in a Changing World*, vol. Vol. 1 . Eds. G. Chirici and M. Gianinetto (Firenze, Italy: Associazione Italiana di Telerilevamento (AIT)), 11–14. doi: 10.978.88944687/17

Hoobler, B. M., Vance, G. F., Hamerlinck, J. D., Munn, L. C., and Hayward, J. A. (2003). Applications of land evaluation and site assessment (LESA) and a geographic information system (GIS) in East Park County, Wyoming. *J. Soil Water Conserv.* 58, 105–112.

Inglese, P., Liguori, G., and de la Barrera, E. (2017). "Ecophysiology and reproductive biology of cultivated cacti," in *Crop ecology, cultivation and uses of cactus pear*, vol. 20 . Eds. M. Taguchi, F. Harinder Makkar, F. Mounir Louhaichi, R. Duffy and D. Moretti, 26–30. Available at: www.fao.org/ Rome, Italy: Computers and Geosciences.

Intrigliolo, D. S., Visconti, F., Bonet, L., Parra, M., Besada, C., Abrisqueta, I., et al. (2018). "Persimmon (Diospyros kaki) trees responses to restrictions in water amount and quality," in *Water Scarcity and Sustainable Agriculture in Semiarid Environment* (New York, USA: Academic Press), 149–177. doi: 10.1016/B978-0-12-813164-0.00008-9

Jain, S., Ranganna, G., Mohapatra, S., Rathod, M., Homeshvari,, Deepak, S. K., et al. (2023). A comprehensive review on Persimmon (Diospyros kaki): Botanical, horticultural, and varietal perspectives. *Int. J. Environ. Climate Change* 13, 4437–4457. doi: 10.9734/ijecc/2023/v13i113624

Jones, K. S., and Costello, L. R. (2007). *Selecting Fruit, Nut, and Berry Crops for Home Gardens in San Mateo and San Francisco Counties*. California, USA: University of California - Division of Agriculture and Natural Resources. doi: 10.3733/ucanr.8261

Khouya, T., Ramchoun, M., Elbouny, H., Hmidani, A., and Alem, C. (2022). Loquat (Eriobotrya japonica (Thunb) Lindl.): Evaluation of nutritional value, polyphenol composition, antidiabetic effect, and toxicity of leaf aqueous extract. *J. Ethnopharmacol.* 296, 115473. doi: 10.1016/j.jep.2022.115473

Kopeć, P. (2024). Climate change—The rise of climate-resilient crops. *Plants* 13, 490. doi: 10.3390/plants13040490

Lanya, I., and Manalu, T. J. (2021). "Remote sensing and GIS application for mapping data base of sustainable agriculture land in Denpasar City," in *IOP Conference Series: Earth and Environmental Science*, vol. Vol. 648, No. 1. (Bristol, England: IOP Publishing), 012003.

Le Houérou, H. N. (1992). *The role of Opuntia cacti in the agricultural development of Mediterranean arid zones. 2nd Int* (Santiago, Chile: Cong. de Tuna y Cochinilla), 22–25.

Leisz, S. J., Lam, N. T., and Vien, T. D. (2005). Developing a methodology for identifying, mapping and potentially monitoring the distribution of general farming system types in Vietnam's northern mountain region. *Agric. Syst.* 85, 340–363. doi: 10.1016/j.agsy.2005.06.015

Lin, S., Sharpe, R. H., and Janick, J. (2019). Loquat: botany and horticulture. *Hortic. Rev.* 47, 233–274. doi: 10.1002/9780470650752.ch5

Lomas, J. (1988). An agrometeorological model for assessing the effect of heat stress during the flowering and early fruit set on avocado yields. *J. Am. Soc. Hortic. Sci.* 113, 172–176. doi: 10.21273/JASHS.113.1.172

Lovatt, C. J. (1990). *Factors affecting fruit set/early fruit drop in avocado* Vol. 74 (Ventura, California, USA: California Avocado Society Yearbook), 193–199.

Lu, G., and Wong, D. W. (2008). An adaptive inverse-distance weighting spatial interpolation technique. *Comput. Geosci.* 34, 1044–1055. doi: 10.1016/j.cageo.2007.07.010

Luedeling, E. (2012a). Climate change impacts on winter chill for temperate fruit and nut production: A review. *Scientia Hortic.* 144, 218–229. doi: 10.1016/j.scienta.2012.07.011

Luedeling, E. (2012b). Gassner A., Partial Least Squares Regression for analyzing walnut phenology in California. *Agric. For. Meteorol.* 158–159, 43–52. doi: 10.1016/j.agrformet.2011.10.020

Luedeling, E., and Brown, P. H. (2011). A global analysis of the comparability of winter chill models for fruit and nut trees. *Int. J. Biometeorol.* 55, 411–421. doi: 10.1007/s00484-010-0352-y

Luedeling, E., Girvetz, E. H., Semenov, M. A., and Brown, P. H. (2011). Climate change affects winter chill for temperate fruit and nut trees. *PloS One* 6, e20155. doi: 10.1371/journal.pone.0020155

Maldera, F., Carone, V., Castellarnau, I. I., Vivaldi, G. A., and Camposeo, S. (2023). Available PAR, growth and yield of a super high-density almond orchard are influenced by different row orientations. *Agronomy* 13 (3), 874. doi: 10.3390/agronomy13030874

Martínez, M. L., Labuckas, D. O., Lamarque, A. L., and Maestri, D. M. (2010). Walnut (Juglans regia L.): genetic resources, chemistry, by-products. *J. Sci. Food Agric.* 90, 1959–1967. doi: 10.1002/jsfa.4059

McGranahan, G., and Leslie, C. (2012). *Walnut In Fruit Breeding*. Eds. M. L. Badenes and D. H. Byrne (New York: Springer-Verlag), 827–846.

Mickelbart, M. V., Melser, S., and Arpaia, M. L. (2007). Salinity-induced changes in ion concentrations of 'Hass' avocado trees on three rootstocks. *J. Plant Nutr.* 30, 105–122. doi: 10.1080/01904160601055137

Ministry of Agriculture of Greece (2019). *The Greek agriculture in numbers: Basic characteristics*. Available online at: http://www.minagric.gr/ (Accessed 22/04/2024).

Miranda, C., Urrestarazu, J., and Gonzaga Santesteban, L. (2021). 2020. fruclimadapt: An R package for climate adaptation assessment of temperate fruit species. *Comput. Electron. Agric.* 180, 105879. doi: 10.1016/j.compag.2020.105879

Muñoz-Flores, H. J., Sáenz-Reyes, J. T., García-Sánchez, J. J., Hernández-Máximo, E., and Anguiano-Contreras, J. (2011). Areas with potential for commercial timber plantations of Pinus pseudostrobus Lindl. and Pinus greggii Engelm. in Michoacan. *Rev. Mexicana Cienc. Forestales* 2, 29–44. doi: 10.4236/ojf.2016.65036

NASS, U. (2020). *Quick Stats Dep Agric Natl Agric Stat Serv*. Available online at: https://quickstats.nass.usda.gov (Accessed 22 April 2024).

Nektarios, N., Kourgialas,, and Zoi Dokou, (2021). Water management and salinity adaptation approaches of Avocado trees: A review for hot-summer Mediterranean climate. *Agric. Water Manage.* 252, 106923. doi: 10.1016/j.agwat.2021.106923

Openstreetmap.org. (2024). Available online at: https://www.openstreetmap.org (Accessed 22 April 2024).

Pan, G., and Pan, J. (2012). "Research in crop land suitability analysis based on GIS," in *Computer and computing technologies in agriculture V: 5th IFIP TC 5/SIG 5.1 conference, CCTA 2011, Beijing, China, October 29-31, 2011, Proceedings, Part II 5* (Germany: Springer Berlin Heidelberg), 314–325.

Payghamzadeh, K., and Kazemitabar, S. K. (2011). *In vitro* propagation of walnut-A review. *Afr. J. Biotechnol.* 10, 290–311.

Perucho, R. (2015). "El cultivo del caqui. Antecedentes e importancia económica," in *El Cultivo del Caqui*. Eds. M. L. Badenes, D. S. Intrigliolo, A. Salvador and A. Vicent (Generalitat Valenciana, Valencia, Spain), p.17–p.33.

Pillsbury, A. F., and Huberty, M. R. (1944). *Drainage of avocado orchards on terrace and upland soils* (Berkeley, California, USA: University of California, College of Agriculture, Agricultural Experiment Station).

Polat, A. A. (2007). Loquat production in Turkey: Problems and solutions. *Eur. J. Plant Sci. Biotechnol.* 1, 187–199. doi: 10.17660/ActaHortic.2007.750.4

Ponder, F. (2004). Soils and nutrition management for black walnut. *United States Department Agric. For. Service Gen. Tech. Rep. Nc* 243, 71.

Prevenda, M. (2020). Producția de fructe, afectată de înghețurile târzii. Available at: https://www.revistafermierului.ro/din-revista/horticultura/item/4412-productia-de-fructe-afectata-de-ingheturile-tarzii.html (accessed 5 August 2024).

Prisa, D. (2021). Opuntia ficus-indica the key plant in climate change: characteristics, cultivation and uses. *GSC Biol. Pharm. Sci.* 17, 094–105. doi: 10.30574/gscbps

Radha, K. O., and Khwarahm, N. R. (2022). An Integrated Approach to Map the Impact of Climate Change on the Distributions of Crataegus azarolus and Crataegus monogyna in Kurdistan Region, Iraq. *Sustainability* 14, 14621. doi: 10.3390/su142114621

Ramírez-Mejía, D., Levers, C., and Mas, J. F. (2022). Spatial patterns and determinants of avocado frontier dynamics in Mexico. *Regional Environ. Change* 22, 28. doi: 10.1007/s10113-022-01883-6

Ramos, D. E. (1997). *Walnut production manual (Vol. 3373)* (California, USA: UCANR publications).

Raparelli, E., and Bajocco, S. (2023). Locations of Xylella fastidiosa infections in Apulia (Italy). figshare. Dataset. doi: 10.6084/m9.figshare.22220872.v1

Rohela, G. K., Shukla, P., Kumar, R., and Chowdhury, S. R. (2020). Mulberry (Morus spp.): An ideal plant for sustainable development. *Trees Forests People* 2, 100011. doi: 10.1016/j.tfp.2020.100011

Ros, E. (2010). Health benefits of nut consumption. *Nutrients* 2, 652–682. doi: 10.3390/nu2070652

Salazar-Garcia, S., Zamora-Cuevas, L., and Vega-López, R. J. (2005). Update on the avocado industry of Michoacán, México. *California Avocado Soc Yrbk* 87, 31–44.

Salgado, E., and Cautín, R. (2008). Avocado root distribution in fine and coarse-textured soils under drip and microsprinkler irrigation. *Agric. Water Manage.* 95, 817–824. doi: 10.1016/j.agwat.2008.02.005

Santos, M., Fraga, H., Belo-Pereira, M., and Santos, J. A. (2019). Assessment of growing thermal conditions of main fruit species in Portugal based on hourly records from a weather station network. *Appl. Sci.* 9, 3782. doi: 10.3390/app9183782

Saponari, M., Giampetruzzi, A., Loconsole, G., Boscia, D., and Saldarelli, P. (2019). Xylella fastidiosa in olive in apulia: Where we stand. *Phytopathology* 109, 175–186. doi: 10.1094/PHYTO-08-18-0319-FI

Scedei, D. N., Iordănescu, O. A., Duma, A., Beinşan, C., Alda, S., Alda, L. M., et al. (2020). *Behavior of walnut biotypes (Juglans regia L.), from Cenei, Timis county*. Timisoara, Romania: Journal of Horticulture, Forestry and Biotechnology.

Scortichini, M. (2020). The multi-millennial olive agroecosystem of Salento (Apulia, Italy) threatened by Xylella fastidiosa subsp. pauca: A working possibility of restoration. *Sustainability* 12, 6700. doi: 10.3390/su12176700

Selim, S., Koc-San, D., Selim, C., and San, B. T. (2018). Site selection for avocado cultivation using GIS and multi-criteria decision analyses: Case study of Antalya, Turkey. *Comput. Electron. Agric.* 154, 450–459. doi: 10.1016/j.compag.2018.09.038

Shadeed, S. M., Abboushi, A. M., and Almasri, M. N. (2017). Developing a GIS-based agro-land suitability map for the Faria agricultural catchment, Palestine. *Int. J. Global Environ. Issues* 16, 190–204. doi: 10.1504/IJGENVI.2017.083423

Solar, A. (1989). "Phenological and pomological characteristics of walnut cultivars in northeastern Slovenia," in *I International Symposium on Walnut Production 284*. Budapest, Hungary, 167–174.

Sommaruga, R., and Eldridge, H. M. (2021). Avocado production: Water footprint and socio-economic implications. *EuroChoices* 20, 48–53. doi: 10.1111/1746-692X.12289

Steduto, P., and Todorovic, M. (2001). "The Agro-ecological characterisation of Apulia region (Italy): Methodology and experience," in *Soil resources of Southern and Eastern Mediterranean countries*, vol. 2001 . Eds. P. Zdruli, P. Steduto, C. Lacirignola and L. Montanarella (CIHEAM, Bari), 143–158.

Steinhardt, R. (1991). Estimating yield loss of avocado trees due to a cut in water application. *Hassade* 71, 1363–1366.

Sugihara, G., and May, R. M. (1990). Applications of fractals in ecology. *Trends Ecol. Evol.* 5, 79–86. doi: 10.1016/0169-5347(90)90235-6

Tamam, A. (2008). Morphological and moleculer characterization of some avocado (Persea americana mill.) cultivars (in Turkish, master thesis). University of Cukurova, Institute of Natural and Applied Sciences, Department of Biotecnology, Adana, Turkey.

Vinceti, B., Loo, J., Gaisberger, H., van Zonneveld, M. J., Schueler, S., Konrad, H., et al. (2013). Conservation priorities for Prunus africana defined with the aid of spatial analysis of genetic data and climatic variables. *PloS One* 8 (3). doi: 10.1371/journal.pone.0059987

Visconti, F., Intrigliolo, D. S., Quinones, A., Tudela, L., Bonet, L., and de Paz, J. M. (2017). Differences in specific chloride toxicity to Diospyros kaki cv."Rojo Brillante" grafted on D. lotus and D. virginiana. *Scientia Hortic.* 214, 83–90. doi: 10.1016/j.scienta.2016.11.025

Wahba, M. M., Darwish, K. M., and Awad, F. (2007). *Suitability of specific crops using MicroLEIS program in Sahal Baraka, Farafra oasis, Egypt*. Wallingford, UK: CAB International.

Wang, Y. P., Handoko, J. R., and Rimmington, G. M. (1992). Sensitivity of wheat growth to increased air temperature for different scenarios of ambient CO2 concentration and rainfall in Victoria, Australia—a simulation study. *Clim. Res.* 2, 131–149. doi: 10.3354/cr002131

Whiley, A. W., and Winston, E. C. (1987). Effect of temperature at flowering on varietal productivity in some avocado growing areas in Australia. *South Afr. Avocado Growers' Assoc. Yearbook* 10, 45–47.

White, S. M., Bullock, J. M., Hooftman, D. A. P., and Chapman, D. S. (2017). Modelling the spread and control of Xylella fastidiosa in the early stages of invasion in Apulia, Italy. *Biol. Invasions* 19, 1825–1837. doi: 10.1007/s10530-017-1393-5

Wilkinson, J. (2005). *Nut grower's guide: the complete handbook for producers and hobbyists* (Clayton, Victoria, Australia: Landlinks Press). doi: 10.1071/9780643093096

Wolstenholme, B. N. (2013). "Ecology: climate and soils," in *The Avocado: Botany, Production and Uses*, *2nd ed.* Eds. B. Schaffer, B. N. Wolstenholme and A. W. Whiley (Wallingford, Oxfordshire, UK: CABI), 86–100.

Wu, L., and Dodge, L. (2005). *Landscape plant salt tolerance selection guide for recycled water irrigation* (Endowment Fund).

Yilmaz, C. (2021). *Soil Management and Fertilization in Walnut. Walnut* (Ankara, Turkey: iksad publishing house).

Zhang, Z., Chang, Q., Zhu, M., Huang, Y., Ho, W. K., and Chen, Z. Y. (2001). Characterization of antioxidants present in hawthorn fruits. *J. Nutr. Biochem.* 12, 144–152. doi: 10.1016/S0955-2863(00)00137-6

Zhu, X. (2016). "Chapter 1, 2," in *GIS for Environmental Applications: A Practical Approach* (Routledge, New York), 471, ISBN: . doi: 10.4324/9780203383124