



Forest accessibility, Madonie mountains (northern Sicily, Italy): implementing a GIS decision support system

Sebastiano Sferlazza, Antonino Maltese, Giuseppe Ciruolo, Gino Dardanelli, Federico Guglielmo Maetzke & Donato Salvatore La Mela Veca

To cite this article: Sebastiano Sferlazza, Antonino Maltese, Giuseppe Ciruolo, Gino Dardanelli, Federico Guglielmo Maetzke & Donato Salvatore La Mela Veca (2021) Forest accessibility, Madonie mountains (northern Sicily, Italy): implementing a GIS decision support system, Journal of Maps, 17:2, 464-473, DOI: [10.1080/17445647.2021.1962751](https://doi.org/10.1080/17445647.2021.1962751)

To link to this article: <https://doi.org/10.1080/17445647.2021.1962751>



© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



View supplementary material [↗](#)



Published online: 13 Sep 2021.



Submit your article to this journal [↗](#)



View related articles [↗](#)



View Crossmark data [↗](#)



Forest accessibility, Madonie mountains (northern Sicily, Italy): implementing a GIS decision support system

Sebastiano Sferlazza ^a, Antonino Maltese ^b, Giuseppe Ciralo ^b, Gino Dardanelli ^b,
Federico Guglielmo Maetzke ^a and Donato Salvatore La Mela Veca ^a

^aDepartment of Agricultural, Food and Forest Sciences, University of Palermo, Palermo, Italy; ^bDepartment of Engineering, University of Palermo, Palermo, Italy

ABSTRACT

Valorisation and sustainable exploitation of woody biomass from cultivation interventions might be an important opportunity to track alternative development trails for rural communities in natural protected areas. The governance of Mediterranean protected areas is characterized by overlapping, sometimes conflicting institutions, stakeholders and regulations, causing negative impacts on decision-making processes. We present an open source GIS-based decision support system tool for mapping forest accessibility and optimizing woody biomass extraction. Two models were implemented to support forest managers during the decision-making process in designing and managing wood-energy supply chains. The optimal grid resolution to run the models was determined via a Least Cost Path analysis. The models were executed at different scales, performing satisfactorily when distances between recorded and modelled paths were lower than the grid unit. The higher the scale, the more the percentile of distances lower than the grid unit. The models were validated in Madonie mountains, Sicily, Italy.

ARTICLE HISTORY

Received 28 December 2020
Revised 15 July 2021
Accepted 15 July 2021

KEYWORDS

Open source DSS tool;
Geographic Information System; algorithm scripting;
Least Cost Path analysis;
woody biomass energy;
Mediterranean protected areas



1. Introduction

Since the 1980s, many Decision Support Systems (DSS) have been developed for modelling and managing forest sub-systems, including goods production, services supplying, hydrogeological protection and recreational activities (e.g. Packalen et al., 2013; Reynolds, 2005; Segura et al., 2014), whose interaction at social, economic and ecological levels represents the integrated forest management system. Among these, first GIS-based DSS extended the DSS functionalities to analyse the forest patterns, processes and relationships (e.g. Li & Zhao, 2006; Zeng et al., 2007). Most of the Mediterranean forests are protected areas including Natura 2000 sites, national and regional parks and/or reserves. The governance of protected areas is characterized by overlapping and, sometimes, conflicting institutions, stakeholders and regulations, having a negative impact on decision-making processes. The main issues are as follows:

- (i) high fragmentation of the legal framework in several public administrative levels (national, regional and municipal) and private (private owners), resulting in increasing harvesting costs, sometimes economically unsustainable (ForBioEnergy Project, 2017);

- (ii) low awareness of the advantages offered by cooperatives of forest owners (ForBioEnergy Project, 2017);
- (iii) a fewer executive forest management plans, due to redundant and complicated administrative procedures (Borges et al., 2014; ForBioEnergy Project, 2017);
- (iv) limited awareness of environmental and economic benefits derived from a sustainable forest management;
- (v) limited stakeholders' involvement to improve DSS operational effectiveness (Borges et al., 2014).

In this framework, it is well recognized that DSS can help decision-makers to use natural resources efficiently and to develop integrated management strategies. In particular, the possibility of carrying out cultivation interventions and, therefore, enhancing the residual biomasses is closely linked to the accessibility of forest stands, so it can be analysed with specific tools. The aim of this paper is to present an open-source GIS-based DSS tool tailored to the optimization of the wood-energy supply chain and Forest Integrated management in protected areas, named SOFIA. SOFIA should help local authorities (i.e. policy makers and technicians) of protected

CONTACT Antonino Maltese  antonino.maltese@unipa.it  Department of Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy

 Supplemental data for this article can be accessed <https://doi.org/10.1080/17445647.2021.1962751>

© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

areas in defining effective and environmentally sustainable strategies for the development of wood-energy supply chains at local level. Decision-makers are supported in the following topics:

- forest accessibility assessment: to verify the need for the maintenance of the forest road network;
- biomass supply basin definition: ‘where, how, when and how much’ collecting woody biomass;
- planning strategies proposals aimed to minimize the overall costs and to maximize the benefits for energy production from woody biomass.

For the purpose of this study, the woody biomass is defined as only residues (i.e. logs, branches, leaves, tops, chunks and dead or unwanted stem wood) generated from timber harvesting activities on forests and permanent crops. The use of such residual biomass has become crucial for several reasons. Firstly, it favours employment and profitability of forestry and agricultural activities. Secondly, its removal is the most effective way to prevent wildfires which wreak havoc on local communities and their economies (López-Rodríguez et al., 2009), especially in fire-prone environment. Wildfires, historically, represent a very dangerous threat to forests and other wooded areas in Sicily. Furthermore, wildfires are increasingly projected to worsen under climate change scenarios (La Mela Veca et al., 2016; Sferlazza et al., 2017).

The SOFIA DSS is segregated into two components: (i) the ‘Forest accessibility’ model with the objective of computing and representing the accessibility of forest surfaces, and (ii) the ‘Query’ model with the objective of helping the decision-makers to quantify woody biomass allocations in a given area of interest for wood-energy supply chain optimization.

2. Materials and methods

2.1. Study area

The Madonie mountains (northern Sicily, Italy) were chosen as the pilot area for the implementation of SOFIA (Figure 1). The mountain range extends in a south-eastern direction over a surface of $\approx 1800 \text{ km}^2$, $\approx 311 \text{ km}^2$ of which are forests and $\approx 176 \text{ km}^2$ are permanent crops. The Madonie mountains represent a mosaic of different vegetation and land use types, including deciduous and evergreen broad-leaved forests, coniferous plantations, pasture grasslands, vineyards, olive groves and urban settlements. The territory is characterized by naturalistic and hydrogeological restrictions, since it hosts the Madonie Regional Nature Park, a Regional Nature Reserve and 16 Sites of Community Importance under Habitat Directive. Since the end-1980s, when the Madonie Regional Nature Park established, forest

management has relied on the conservation of biodiversity as a primary objective with silvicultural activities as the secondary goal (Sferlazza et al., 2018).

Maps were designed according to Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007, establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) and its Technical Guidelines Annex I – D2.8.I.1, and according to the Decree 10 November 2011 entitled ‘Adoption of the National Geodetic Reference System’ issued by the Presidency of the Council of Ministers of Italy (Official Gazette General Series n.48 of 27-02-2012 - Ordinary Suppl. n. 37).

2.2. Methodological approach

The DSS SOFIA has been developed in Python embedded in QGIS 3.6.2 open-source software (QGIS Development Team (DT), 2019). The ‘Forest accessibility’ and ‘Query’ models were implemented by exploiting both QGIS processing algorithms and calling algorithms from external applications (GRASS 7.6.1, SAGA 2.3.2 and GDAL 2.4.1) using the built-in Processing modeller. The Processing modeller enabled to generate automated workflows with a simple and easy-to-use Graphical User Interface (GUI). The ‘Forest accessibility’ and ‘Query’ models have been generated as a chain of processes wrapped into a single tool. The forest accessibility is evaluated through the access time, t_A , proposed by Hippoliti (1976), defined as the time required for a forest worker to make a round trip on foot from the nearest road to a given point in the forest. Hippoliti (1976) assumed an average walking speed of 1.11 m s^{-1} on terrain with slopes $\leq 10\%$ and an average walking speed of 0.11 m s^{-1} in terms of difference in altitude on steep terrain with slopes $>10\%$. Table 1 shows the ranges of t_A , as revised by Laschi et al. (2016), reducing the maximum access time to one hour for ‘barely accessible’ areas.

2.3. Input dataset

Vector and raster input datasets include administrative boundaries, land uses, forest types, road network, forest management plan and morphological data computed using a digital elevation model. In summary,

- the Digital Elevation Model (DEM), with 2 m grid resolution, R_S , (Ministero dell’Ambiente e della Tutela del Territorio e del Mare, 2013);
- the road network including roads for trucks (primary and secondary) and forest roads for tractors (<http://www.sitr.regione.sicilia.it/>), classified according to Hippoliti (1976);
- the vector-based classification of the forest and pre-forest communities, according to Regional Inventory of Forests (Regione Siciliana, 2011);

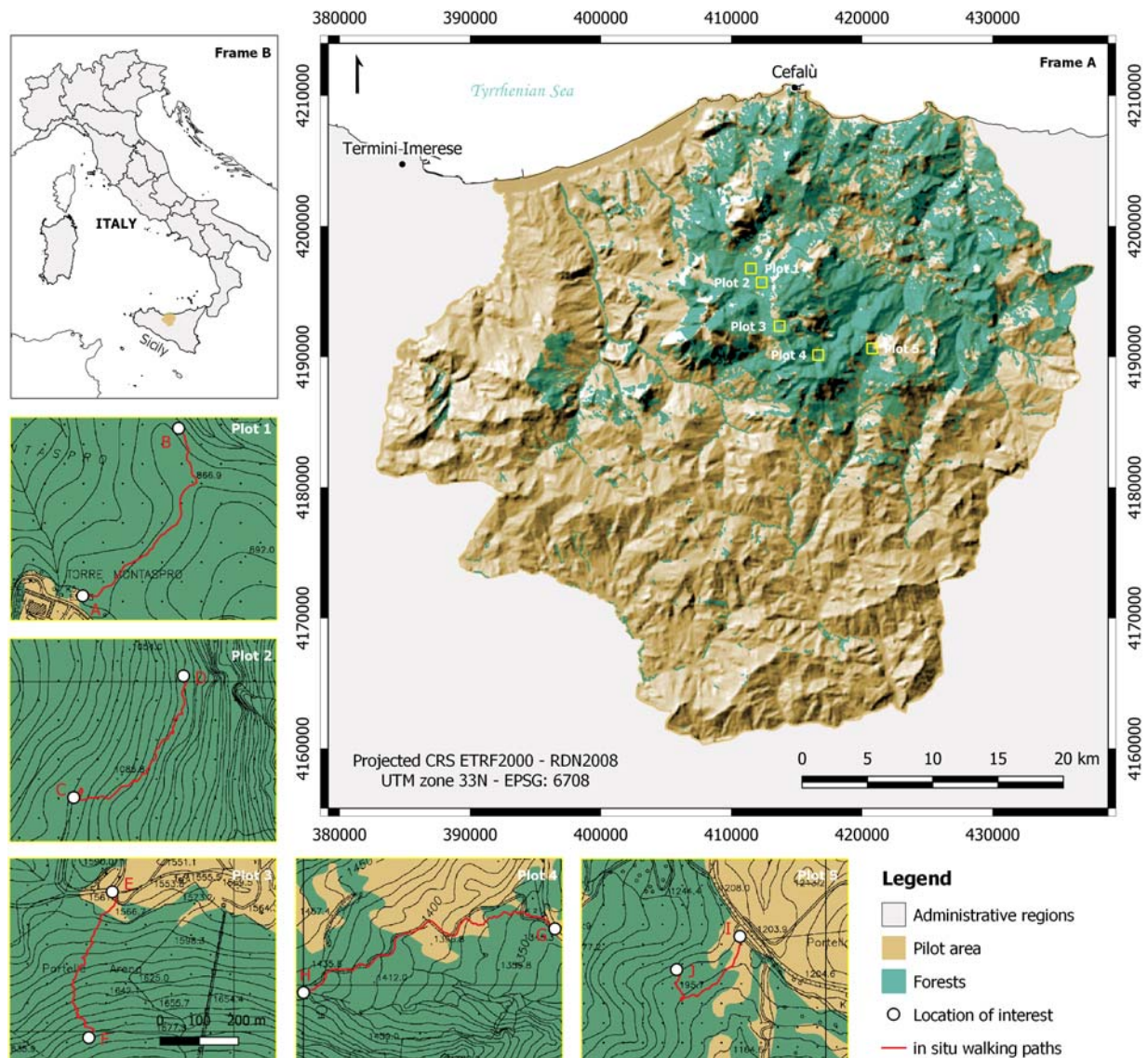


Figure 1. Map of the Madonie mountains in northern Sicily (Frame A), in the green forested area over-imposed the shaded relief extracted by Regional Digital Elevation Model setting the elevation at 315° and the altitude at 45°. Frame B shows the location of pilot area on Italian territory. Five in situ walking paths between harvesting sites and the nearest car release points are represented in plots 1, 2, 3, 4 and 5.

Note. A composition reporting: a map locator of the pilot area in Italy; the forest cover in the pilot area; zoom of the five different walking paths with contour levels.

- the biomass districts vector layer (ForBioEnergy Project, 2018), defining homogeneous areas in terms of woody biomass, road network distribution and local energy needs;
- the park zoning vector layer (<http://www.sitr.regione.sicilia.it/>), reporting any legal restrictions in management and planning;
- the Forest Management Plan (ForBioEnergy Project, 2019) stored in two vector layers. The first layer provides information on the available woody

biomass in the forest parcels, while the second group including the one comes from permanent crops. The different biomass types are characterized by a set of parameters for each parcel/unit (i.e. growing stock volume, total biomass, annual biomass increment, annual biomass increment per unit area).

2.4. Model validation

To determine the suitable R_S ensuring an accurate assessment of accessibility and minimizing the information technology resource demanded by the model, a Least Cost Path (LCP) analysis was carried out. The LCP analyses the most cost-effective path between a source and destination, as a function of the distance travelled and the costs traversed. LCP

Table 1. Classes of access time t_A as defined in the original and revised version of Hippoliti's method.

Classes	t_A (min)	
	(Hippoliti, 1976)	(Laschi et al., 2016)
accessible	< 30	< 30
barely accessible	30 < and ≤ 120	30 < and ≤ 60
inaccessible	> 120	> 60

algorithm generated a cumulative cost surface, which is a raster dataset. The value of each pixel represents the cost per unit distance of crossing that pixel, which depends on the slope gradient. This function has been currently applied in several studies of landscape ecology (e.g. Etherington, 2016) and for modelling of road networks (e.g. Picchio et al., 2018), among other topics.

Five *in situ* walking paths between harvesting sites and nearest car release points on the existing road network (Table 2, Figure 1) were positioned using a Global Navigation Satellite Systems (GNSS) receiver Trimble Recon N324 (by Trimble Inc.) (≈ 2 m accuracy in the absolute method) by recording the walking distance and access time for a round trip. Information about average slope along the path S (%), path type, forest category crossed, walking distance d (m) and access time t_A (min) was also collected/computed for each *in situ* path (Table 2). For each round trip, no repetitions were carried out. These paths were compared with paths generated by the LCP algorithm (QGIS DT, 2019), using a cumulative cost surface at different R_S (2, 4, 10, 20 and 30 m). Coarser R_S were obtained by a pixel aggregate resampling method, starting from the finer R_S . A cumulative time cost surface (s) was modelled, as well as a polyline vector between start- and end-point. The ‘r.grow.distance’ algorithm (GRASS DT, 2019) was applied to generate a raster of the Euclidean distance d_E (m) to the nearest non-null pixel in input layer at the highest R_S .

To evaluate the modelled LCP *versus* the path recorded *in situ*, the Euclidean distances between those paths were compared through statistical tests. The values of d_E characterizing the five paths were tested for normal distribution according to four normality tests: Anderson–Darling, Pearson chi-square, Lilliefors (Kolmogorov–Smirnov) and Shapiro–Francia. Given that data do not follow a normal distribution, the nonparametric Kruskal–Wallis test was applied to compare more than two independent samples and to check whether such samples come from the same distribution (Zar, 2010). A Mann–Whitney–Wilcoxon test with Benjamini and Hochberg (1995) adjustment (BH) allowed a pairwise comparison, assuming a P -value < 0.05 statistical significance. Statistical analyses were carried out in R environment (R Core Team, 2020).

Table 2. Average slope S , walking distance d , access time t_A , path type and forest category crossed of the five *in situ* paths.

Path	S (%)	d (m)	t_A (min)	Path type	Forest category
A–B	12	620	20	partly trail	Holm oak forest
C–D	46	640	25	across forest	Holm oak forest
E–F	31	550	25	across forest	Beech forest
G–H	21	870	25	partly trail	Beech forest
I–J	17	400	20	across forest	Plantation

3. Results

The main algorithms implemented in the Forest accessibility and Query models are described in detail.

3.1. Forest accessibility and Query model architecture

The ‘Forest accessibility’ model allows evaluating the pattern of the forest accessibility (Figure 2). The end-users are able to visualize spatial data, carry out statistical analysis, and make queries. Thus, the tool can be used to assist them in the definition and application of a sustainable woody biomass exploitation plan. In addition, the end-users could suggest forest road network improvement to satisfy multiple needs related to: (i) wildfire fighting activities (Laschi et al., 2019); (ii) ensure continuity of timber harvesting operations (Akay et al., 2020); (iii) improve the safety and productivity of forest operations, as well as to minimize negative environmental impacts (Marchi et al., 2018); and (iv) to support the maintenance of ecosystem services (Picchio et al., 2018). Forest accessibility mapping is concerned not only with bioenergy and road network planning, but also with the recreational potential of protected areas. Accessibility is a key aspect and determines the opportunity for people to move from the urban areas to nature parks and reserves for the fulfilment of outdoor leisure activities demand, e.g. hiking, Nordic walking, climbing, mountain biking and skiing.

The main steps necessary for the model application are described below. Firstly, a raster layer representing the cost of crossing a pixel as function of the slope gradient (the ‘unit cost map’) is computed as follows:

- Slope map generation and reclassification. The ‘r.slope.aspect’ algorithm (GRASS DT, 2019) was applied to generate a slope percentage (s) from the DTM in single-precision floating-point format ($fcell$). Slope values higher than 70% were considered as an upper limit for walking. Moreover, the International Labour Organization (1998) suggests that the traditional ground-based forestry equipment should not be operated on a slope exceeding 50% for the worker’s safety.
- Differential levelling map generation. Differential levelling (d) was computed as follows:

$$d = (R_S^2 + s^2 R_S^2)^{0.5} \quad (1)$$

- Unit cost map generation. The average walking speed, v_w , on flat or gently sloped terrain ($s \leq 10\%$) was assumed equal to 1.11 m s^{-1} , while on steep terrain ($s > 10\%$) it was assumed equal to 0.11 m s^{-1} in terms of difference in altitude, thus, a raster of the pixel crossing time (t_{pc}) was

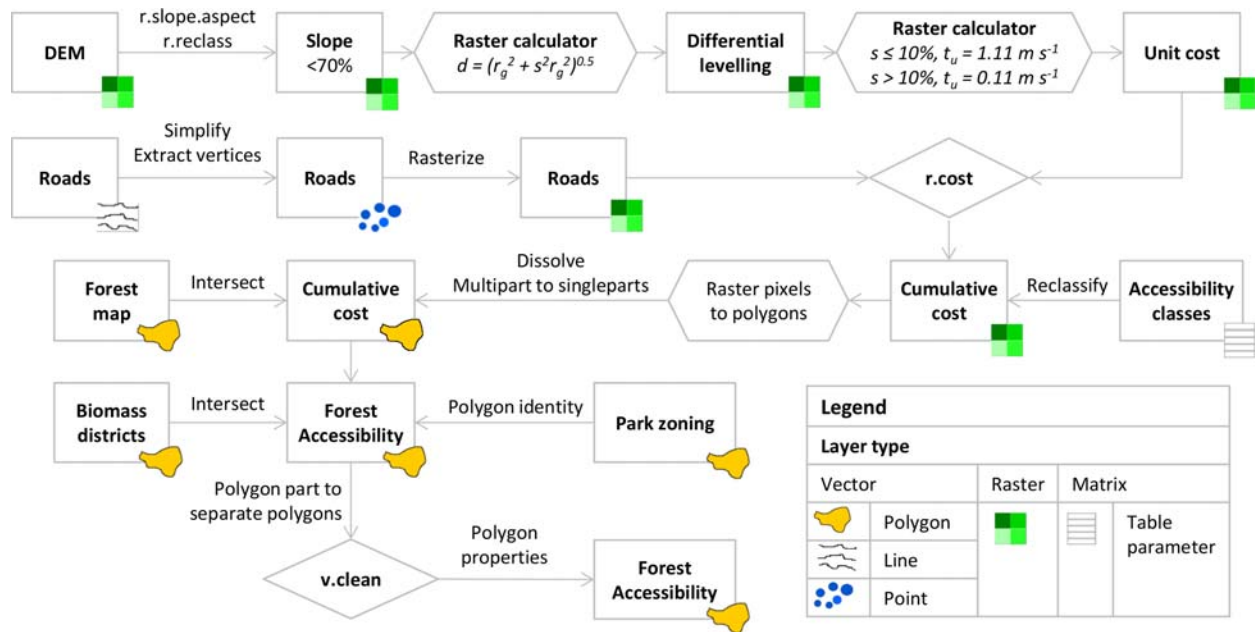


Figure 2. Architecture of the Forest accessibility model.

Note. Workflow describing the algorithms' sequence in the model to assess the forest accessibility.

calculated as follows:

$$t_{pc} = \frac{d}{v_u} \quad (2)$$

Secondly, a Boolean 'road network' representing the presence/absence of roads was rasterized from a corresponding vector layer:

- Cumulative cost map generation and reclassification. The 'r.cost' algorithm (GRASS DT, 2019) allows generating a raster cumulative cost of moving based on the 'Knight's move' option, from a raster point road network to a pixel on the unit cost surface. The map was reclassified according to a revised version of Hippoliti's method (Table 1).

Hence, the reclassified cumulative cost was vectorized as polygon geometries. The GIS-based DSS have been applied to define the forest accessibility of the study area. Forest accessibility map, see 'Main Map', was obtained by intersecting the previously computed cumulative cost map with the remaining input vector layers. Step by step

- Forest accessibility map generation. The 'intersect' SAGA algorithm (Conrad et al., 2015) allows overlaying the features of the forest map and the cumulative cost map, and combining features from the forest accessibility layer and the biomass districts layer. Multipart geometries were converted into single part geometries.

- The 'rmarea' tool of the 'v.clean' algorithm (GRASS DT, 2019) allows merging all geometries characterized by a threshold area $\leq 5000 \text{ m}^2$ to the adjacent polygon sharing the longest boundary. The threshold is assumed as minimum patch size according to the Italian National Forest Inventory and consistent with the FRA 2000 definition (FAO, 2000).

The 'Query' model aims to (i) enable a smart access at the Forest Management Plan database; (ii) determine accurately the available woody biomass exploitable for energy production purposes in an area of interest (AOI). The architecture of the model is depicted in Figure 3. This model recalculates the biomass parameters related to a selected AOI by end-user.

The model is composed of two independent sub-models, which can be run individually by deactivating the other one. As the first step, three vector layers are used as inputs. The first of these includes biomass parameters associated with forest parcels (i.e. management unit), the second includes the ones associated with permanent crops, while the last one represents a specific zone susceptible to harvesting for bioenergy purposes (i.e. AOI). The common steps of both sub-models are described below:

- After clipping the two input layers over the AOI, the 'polygon parts to separate polygons' SAGA algorithm (Conrad et al., 2015) allowed splitting multipart geometries into separate geometries; the inner and outer rings were included in the process.

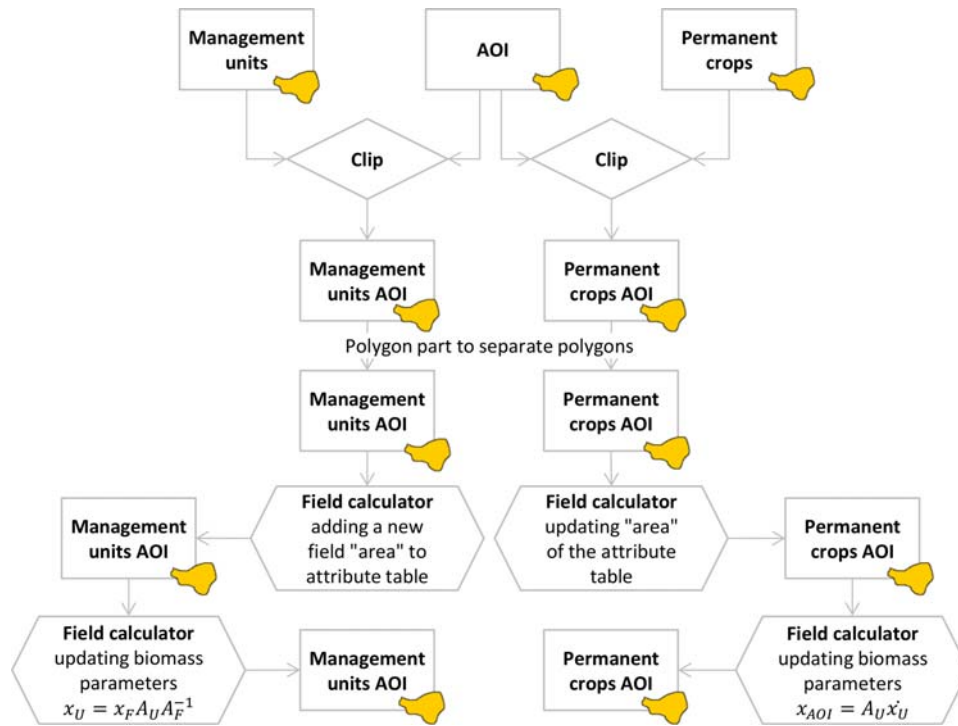


Figure 3. Architecture of the Query model.

Note. Workflow describing the algorithms' sequence in the model to determine the available woody biomass for energy production in a given area of interest.

- Then, the surface area (A_{U_i}) of each i th parcel/unit was computed/updated for both the previous outputs.

We updated biomass parameters associated with specific forest parcel as follows:

$$x_{U_i} = x_{F_i} A_{U_i} A_{F_i}^{-1} \quad (3)$$

Henceforth, the two workflows differentiated as follows:

where x_{U_i} ($m^3 ha^{-1}$) is the updated biomass parameter value in relation to the current extension of the i th

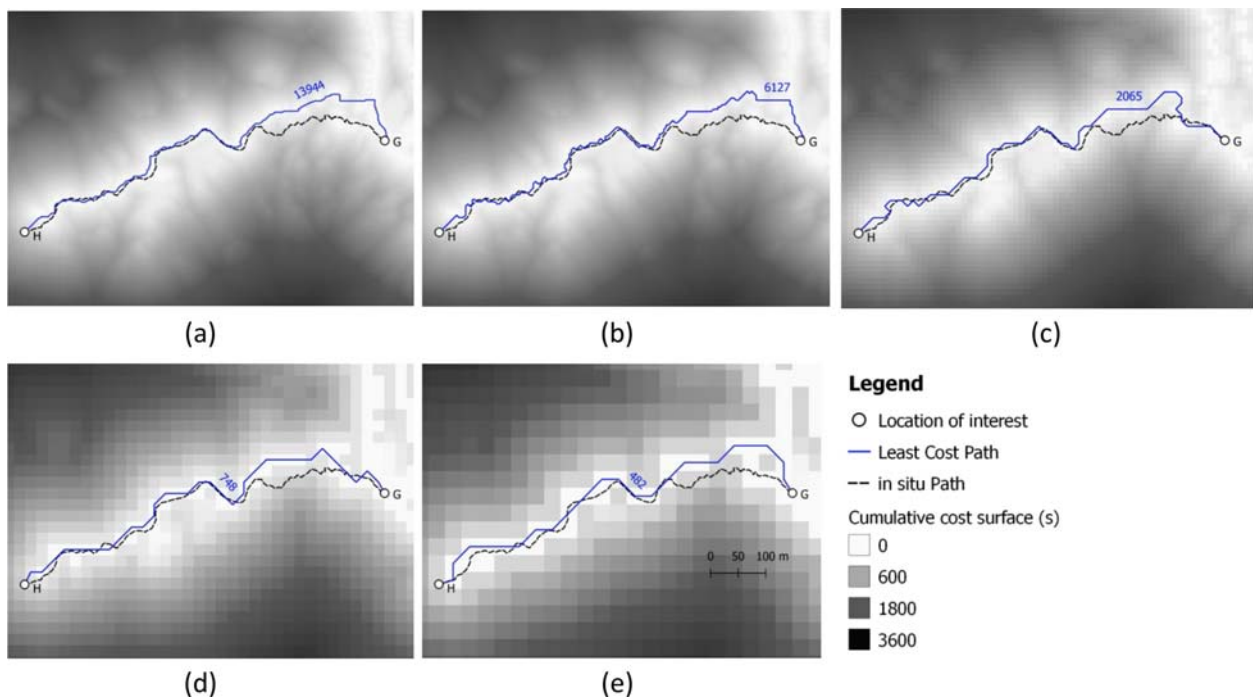


Figure 4. Effects of grid $R_5 = 2, 4, 10, 20$ and 30 m (a, b, c, d and e panels, respectively) of cumulative cost surface on the least cost paths modelling between the locations G and H. The LCP is shown in blue; the path recorded via GNSS is shown in black. Note that the least cost distance value is shown above each path.

Note. A walking path positioned via a Global Navigation Satellite Systems receiver, compared to five modelled walking paths resulting from cumulative cost surfaces at decreasing grid resolutions.

parcel, x_{Fi} (m^3ha^{-1}) is the former biomass parameter value related to the previous extension of the i th parcel, A_{Ui} (ha) is the updated surface area of the i th parcel and A_{Fi} (ha) is the former surface area of the i th parcel.

- We updated biomass parameters related to a specific permanent crop unit as follows:

$$x_{Ui} = A_{Ui}x_{Fi} \quad (4)$$

where x_{Ui} ($\text{m}^3\text{year}^{-1}$) is the updated biomass parameter value in relation to the current extension of the i th unit, x_{Fi} ($\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) is the biomass parameter value per unit surface area of the i th unit.

3.2. Least Cost Path analysis

The cheapest walking paths between pairs of locations were obtained via a LCP analysis for a given cumulative cost surface and for varying R_S . The cumulative cost surface was obtained at 2, 4, 10, 20 and 30 m R_S . Five pairs of start to end points locations were tested, namely, A – B, C – D, E – F, G – H and I – J. The GIS-based DSS do not model differently the one-way from the way-back. The least cost distance, i.e. the total cost of crossing the space between start and end points, reduces as grid resolution decreases (Figure 4) (Etherington, 2016). A 30 m R_S minimizes the median absolute deviation (MAD) of the average Euclidean distances between modelled and *in situ* path on three out of the five pairs, i.e. C – D, E – F and I – J. Result of running the LCP for path G-H produced lowest MAD values between modelled and *in situ* paths, i.e. varying between 4.4 and 10.5 m depending on R_S . The modelled path at 10 m R_S largely overlaps with the path recorded *in situ* via GNSS.

Statistically, significant differences were found among distances modelled at varying R_S between pairs A – B, C – D and E – F, while the distances between the two paths (G – H and I – J) belong to the same population (or populations with equal median), thus can be assumed as statistically not significant (with $P < 0.05$) (Table 3).

The Mann–Whitney–Wilcoxon test (for paired samples) ranks the absolute values of the distances between the paired GNSS recorded and GIS-based

Table 3. Kruskal–Wallis statistics (chi square, χ^2 ; degree of freedom, *d.f.*; probability level, *P*) on the d_E dataset for the five paths at five different R_S .

Path	χ^2	<i>d.f.</i>	<i>P</i>
A–B	355.85	298	0.012*
C–D	403.31	330	0.004*
E–F	217.65	167	0.005*
G–H	149.35	141	0.299
I–J	170.47	206	0.966

*statistically significant at $P < 0.05$.

DSS modelled paths. Starred values in Table 4 indicate distances statistically significant different from 0. The path G – H shows significant differences if one of the compared resolutions is 20 or 30 m, while the path I – J shows significant differences only versus $R_S = 30$ m.

In a raster-based modelling, Euclidean distances lower than R_S are not appreciable. A relative distance, $d_{RS}(-)$, was defined as the rounding to the next integer of the distance between a generic vertex/node of the modelled path and the *in situ* reference path rationed to grid resolution: $d_{RS} = dR_S^{-1}$. The model was assumed to perform satisfactory at a given resolution if $d_{RS} \leq 1$. In Table 5 the relative distance d_{RS} is reported for varying R_S for classes of distances in the ascending order, from 5th to 95th percentile. The coarser the grid resolution, the more the percentile of relative distances lower than unit. For instance, an accuracy compatible with R_S is achieved at 20 m between 10th percentile (I – J path) and 90th percentile (G – H path), as well as at 30 m resolution between 25th percentile (C – D path) and 95th percentile (G – H path).

4. Discussion and conclusions

The functionalities of an open-source GIS-based DSS tool designed for mapping forest accessibility and optimizing woody biomass extraction were presented. In the last decades, several studies have introduced models capable of matching forest features to a set of technologies, systems and models aiming at managing forest ecosystems for several purposes, including protective, productive and services functions. Some of these models were developed with proprietary software (Freppaz et al., 2004; Li & Zhao, 2006; López-Rodríguez et al., 2009; Zeng et al., 2007). In contrast, our models are developed on free and open source GIS software (Marano et al., 2019; Picchio et al.,

Table 4. Post-hoc pairwise comparisons for assessing R_S effect on resulting modelling accuracy using Mann–Whitney–Wilcoxon test (P -value < 0.05 , BH adjustment method).

Path	R_S (m)	4	10	20	30
A-B	2	0.161	7.5e ^{-08*}	2.2e ^{-06*}	0.277
	4		1.2e ^{-10*}	5.7e ^{-10*}	0.002*
	10			0.161	1.5e ^{-11*}
	20				5.6e ^{-10*}
C-D	2	0.86	0.86	0.86	0.86
	4		0.92	0.92	0.86
	10			0.92	0.86
	20				0.86
E-F	2	0.52	0.52	0.018*	0.012*
	4		0.735	0.055	0.018*
	10			0.115	0.018*
	20				0.52
G-H	2	0.633	0.066	1.4e ^{-05*}	1.2e ^{-11*}
	4		0.053	4.2e ^{-06*}	1.3e ^{-12*}
	10			3.6e ^{-05*}	8.5e ^{-14*}
	20				9.8e ^{-06*}
I-J	2	0.771	0.771	0.771	0.005*
	4		0.919	0.919	0.005*
	10			0.919	0.005*
	20				0.005*

*statistically significant at $P < 0.05$.

Table 5. Relative distance d_{RS} for varying R_S (y-axis) vs. percentile of d_{E} , P_{dE} (x-axis), for the paths A – B, C – D, E – F, G – H and I – J.

$P_{dE} \rightarrow$	5th	10th	25th	50th	75th	90th	95th	5th	10th	25th	50th	75th	90th	95th
$R_S \downarrow$														
2	2	5	13	21	38	44	47	1	2	13	32	45	51	52
4	2	3	7	14	21	24	24	1	1	6	16	22	25	26
10	1	1	2	2	4	5	5	0	1	2	6	9	10	10
20	1	1	1	1	2	2	3	0	1	1	3	4	5	5
30	1	1	1	1	2	2	2	0	1	1	2	3	3	3
	(A–B)							(C–D)						(E–F)
2	0	1	1	3	9	16	18	2	8	19	35	42	44	44
4	0	1	1	1	4	8	9	1	4	9	17	21	21	22
10	0	0	0	1	1	3	3	1	2	4	7	8	8	9
20	0	0	0	1	1	1	2	1	2	2	3	4	4	4
30	0	0	0	1	1	1	1	0	1	1	2	2	2	3
	(G–H)							(I–J)						

2018; Puletti et al., 2017; Zambelli et al., 2012) with all the related advantages granted to the user (Steiniger & Hay, 2009). The main innovation proposed regards the definition of a comprehensive approach, based on a DSS tool that can suggest actions and policies to help implement the concept of multipurpose forest management in a protected area. Specifically, we implemented a DSS tool for mapping forest accessibility of a mountain region into a protected area, which represents an asset in decision-making in times of increasing complexity of the issues forester managers face and factors to evaluate. In fact, a few studies addressed the issue of forest accessibility at the landscape scale (Sitzia et al., 2016; Southworth & Tucker, 2001), whereas, in many cases focusing on a local scale (Laschi et al., 2016; Picchio et al., 2018; Puletti et al., 2017).

This tool is able to assess the accessibility of forests according to the Hippoliti (1976) method as revised by Laschi et al. (2016), and plan woody biomass supply basin in a mountain region. A further innovative feature lies in the integration of the forest management plan database on GIS. So, the tool can be used to know where woody biomass is produced or purposely harvested, and also allows determining the compartments or sub-region to be exploited for bioenergy purposes. The model was tested on five walking paths connecting timber harvesting sites and the nearest car release points on the road network accessible to the forest service vehicles. The favourable paths linking pairs of locations were obtained for varying R_S (between 2 and 30 m resolution) via a LCP analysis. Generally, distances smaller than R_S are achieved more frequently with the coarsest R_S (up to 95%, path G – H), distances smaller than R_S never occur for more than 25% of the distances (path G – H) at the finest R_S . Forestry and environment planning in protected areas might benefit of DSS SOFIA. Indeed, it is designed as an easy-to-handle tool for combining simplicity and flexibility by using open source software available for any hardware platform and by requiring only few and easily available input layers, so it can be extended to different regional situations. In conclusion, our tool allows a consortium of neighbouring municipalities in a protected area be able to collaborate in the management of its forests through a plan designed and approved jointly. This is a fundamental approach, often overlooked, for healthy forests and if you want to valorise it for economic and social development of rural communities in the Mediterranean region.

Software

This GIS-based DSS was developed in QGIS 3.6.2. The map was created in QGIS via the Print Composer tool.

Acknowledgements

This study was developed in the framework of Interreg MED Programme, ForBioEnergy project – Forest Bioenergy in the Protected Mediterranean Areas (<https://forbioenergy.interreg-med.eu/>).

Disclosure statement

No potential conflict of interest was reported by the author (s).

Author's contributions

Forest model methodology was contributed by S. Sferlazza (S.S.), F.G. Maetzke (F.G.M.) and D.S. La Mela Veca (D.S.L.); *in situ* data acquisition was done by S.S., D.S.L.; GIS-based DSS design and implementation was done by S.S., G. Dardanelli (G.D.) and A. Maltese (A.M.); S.S., G.D. and A.M. contributed to maps design and creation; F.G.M., D.S.L. and G. Ciraolo (G.C) supervised the work; validation was done by S.S., A.M. G.D. and G.C. All the co-authors wrote, reviewed, edited and approved the manuscript.

Data availability statement

The data that support the findings of this study are openly available in the Knowledge Network for Biocomplexity repository at <https://knb.ecoinformatics.org> at doi: 10.5063/8K77GM.

Geolocation information

Projected Coordinates Reference System (CRS) ETRF2000 – RDN2008 UTM zone 33N – EPSG Geodetic Parameter Dataset: 6708. Extension: West 382782 m; East: 437835 m; South: 4160248 m; North: 4210970 m.

Supplemental materials

Forest accessibility map, see 'Main map', is reported as a supplementary file. Colour palettes were designed to make layers of the forest accessibility and forest category maps informative and easily distinguishable to colour-blind readers (Brewer, 2020).


ORCID


Sebastiano Sferlazza  <http://orcid.org/0000-0002-1333-7417>

Antonino Maltese  <http://orcid.org/0000-0002-2778-4680>

Giuseppe Ciraolo  <http://orcid.org/0000-0001-6627-0175>

Gino Dardanelli  <http://orcid.org/0000-0002-8458-0676>

Federico Guglielmo Maetzke  <http://orcid.org/0000-0001-5688-0420>

Donato Salvatore La Mela Veca  <http://orcid.org/0000-0003-0921-0103>

References

- International Labour Organization. (1998). *Safety and health in forestry work: An ILO code of practice*. <https://www.ilo.org>
- FAO. (2000). *Global forest Resources Assessment 2000 (FRA 2000)*. <http://www.fao.org/forestry/fra/86624/en/>
- Regione Siciliana. (2011). *Inventario Forestale Regione Siciliana 2009 [Forest Inventory of Sicilian Region 2009]*. Comando del Corpo Forestale della Regione Siciliana. Sistema Informativo Forestale [Dataset]. <https://sif.regione.sicilia.it/ilportale/>
- Ministero dell'Ambiente e della Tutela del Territorio e del Mare. (2013). *DTM-LiDAR with 2-m spatial resolution. Sicilia Region [Dataset]*. <http://www.pcn.minambiente.it/mattm/>
- ForBioEnergy Project. (2017). *Barriers and potential solutions for increasing biomass production in the protected areas (Deliverable 3.3.1)*. Forest Bioenergy in the Protected Mediterranean Areas project, Interreg MED Program. <https://forbioenergy.interreg-med.eu/what-we-achieve/deliverable-library/>
- ForBioEnergy Project. (2018). *Geographical identification and description of biomass districts in the protected areas (Deliverable 3.4.1)*. Forest Bioenergy in the Protected Mediterranean Areas project, Interreg MED Program. <https://forbioenergy.interreg-med.eu/what-we-achieve/deliverable-library/>
- ForBioEnergy Project. (2019). *Forest Management Plan of the Biomass district in the protected areas (Deliverable 3.7.1)*. Forest Bioenergy in the Protected Mediterranean Areas project, Interreg MED Program. <https://forbioenergy.interreg-med.eu/what-we-achieve/deliverable-library/>
- GRASS Development Team. (2019). *Geographic Resources Analysis Support System (GRASS) Software (7.6.1)*. Open Source Geospatial Foundation. <https://grass.osgeo.org>
- QGIS Development Team. (2019). *QGIS Geographic Information System (3.6.2)*. Open Source Geospatial Foundation Project. <https://www.qgis.org>
- R Core Team. (2020). *A Language and Environment for Statistical Computing (3.6.3)*. Vienna, AT: R Foundation for Statistical Computing. <https://www.R-project.org>
- Akay, A. O., Akgul, M., Demir, M., & Acar, H. H. (2020). Analysis of factors associated with the amount of forest road reconstruction activity in Turkey: Autoregressive distributed lag modelling approach. *Forest Ecology and Management*, 458, 117800. <https://doi.org/10.1016/j.foreco.2019.117800>
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B Methodological*, 57(1), 289–300. <https://doi.org/10.1111/j.2517-6161.1995.tb02031.x>
- Borges, J. G., Nordstrom, E. M., Garcia-Gonzalo, J., Hujala, T., & Trasobares, A. (Eds.). (2014). Computer-based tools for supporting forest management. The experience and the expertise world-wide. In *Report of Cost Action FP 0804 Forest Management Decision Support Systems* (pp. 1–503). Sveriges lantbruksuniversitet.
- Brewer, C. A. (2020). <http://www.ColorBrewer.org>, retrieved date 31/07/2020
- Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., & Böhner, J. (2015). System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geoscientific Model Development*, 8(7), 1991–2007. <https://doi.org/10.5194/gmd-8-1991-2015>

- Etherington, T. R. (2016). Least-cost modelling and landscape ecology: Concepts, applications, and opportunities. *Current Landscape Ecology Reports*, 1(1), 40–53. <https://doi.org/10.1007/s40823-016-0006-9>
- Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., & Taramasso, A. (2004). Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy*, 26(1), 15–25. [https://doi.org/10.1016/S0961-9534\(03\)00079-5](https://doi.org/10.1016/S0961-9534(03)00079-5)
- Hippoliti, G. (1976). Sulla determinazione delle caratteristiche della rete viabile forestale [On the determination of the characteristics of the forest road network]. *Italia Forestale e Montana*, 6(1), 242–255.
- La Mela Veca, D. S., Cullotta, S., Sferlazza, S., & Maetzke, F. G. (2016). Anthropogenic influences in land use/land cover changes in Mediterranean Forest Landscapes in Sicily. *Land*, 5(1), 3. <https://doi.org/10.3390/land5010003>
- Laschi, A., Foderi, C., Fabiano, F., Neri, F., Cambi, M., Mariotti, B., & Marchi, E. (2019). Forest road planning, construction and maintenance to improve forest fire fighting: A review. *Croatian Journal of Forest Engineering*, 40(1), 207–219. <http://www.crojfe.com/archive/volume-40-no-1/forest-road-planning-construction-and-maintenance-to-improve-forest-fire-fighting-a-review/>
- Laschi, A., Neri, F., Brachetti Montorselli, N., & Marchi, E. (2016). A methodological approach exploiting modern techniques for forest road network planning. *Croatian Journal of Forest Engineering*, 37(2), 319–331. <http://www.crojfe.com/archive/volume-37-no-2/a-methodological-approach-exploiting-modern-techniques-for-forest-road-network-planning/>
- Li, F., & Zhao, Y. (2006). Development of a GIS-based decision-support system of forest resource management. *Science in China, Series E: Technological Sciences*, 49(1), 76–85. <https://doi.org/10.1007/s11431-006-8109-x>
- López-Rodríguez, F., Pérez Atanet, C., Cuadros Blázquez, F., & Ruiz Celma, A. (2009). Spatial assessment of the bioenergy potential of forest residues in the western province of Spain, Cáceres. *Biomass and Bioenergy*, 33(10), 1358–1366. <https://doi.org/10.1016/j.biombioe.2009.05.026>
- Marano, G., Langella, G., Basile, A., Cona, F., De Michele, C., Manna, P., Teobaldelli, M., Saracino, A., & Terribile, F. (2019). A geospatial decision support system tool for supporting integrated forest knowledge at the landscape scale. *Forests*, 10(8), 690. <https://doi.org/10.3390/f10080690>
- Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P. S., McEwan, A., Brink, M., & Laschi, A. (2018). Sustainable forest operations (SFO): A new paradigm in a changing world and climate. *Science of the Total Environment*, 634, 1385–1397. <https://doi.org/10.1016/j.scitotenv.2018.04.084>
- Packalen, T., Marques, A. F., Rasinmäki, J., Rosset, C., Mounir, F., Rodriguez, L. C. E., & Nobre, S. R. (2013). Review. A brief overview of forest management decision support systems (FMDSS) listed in the FORSYS wiki. *Forest Systems*, 22(2), 263–269. <http://doi.org/10.5424/fs/2013222-03192>
- Picchio, R., Pignatti, G., Marchi, E., Latterini, F., Benanchi, M., Foderi, C., Venanzi, R., & Verani, S. (2018). The application of two approaches using GIS technology implementation in forest road network planning in an Italian mountain setting. *Forests*, 9(5), 277. <https://doi.org/10.3390/f9050277>
- Puletti, N., Floris, A., Scrinzi, G., Chianucci, F., Colle, G., Michelini, T., Pedot, N., Penasa, A., Scalercio, S., & Corona, P. (2017). CFOR: Un sistema di supporto alle decisioni per le foreste in Calabria. *Forest@*, 14(2), 135–140. <https://doi.org/10.3832/efor2363-014>
- Reynolds, K. M. (2005). Integrated decision support for sustainable forest management in the United States: Fact or fiction? *Computers and Electronics in Agriculture*, 49(1), 6–23. <https://doi.org/10.1016/j.compag.2005.02.002>
- Segura, M., Ray, D., & Maroto, C. (2014). Decision support systems for forest management: A comparative analysis and assessment. *Computers and Electronics in Agriculture*, 101, 55–67. <https://doi.org/10.1016/j.compag.2013.12.005>
- Sferlazza, S., Maetzke, F. G., Iovino, M., Baiamonte, G., Palmeri, V., & La Mela Veca, D. S. (2018). Effects of traditional forest management on carbon storage in a Mediterranean holm oak (*Quercus ilex* L.) coppice. *iForest*, 11(2), 344–351. <https://doi.org/10.3832/ifor2424-011>
- Sferlazza, S., Maetzke, F. G., Miozzo, M., & La Mela Veca, D. S. (2017). Resilience of Mediterranean forests to climate change. In B. Fuerst-Bjeliš (Ed.), *Mediterranean identities - environment, society, culture* (pp. 263–282). IntechOpen.
- Sitzia, T., Campagnaro, T., & Grigolato, S. (2016). Ecological risk and accessibility analysis to assess the impact of roads under Habitats Directive. *Journal of Environmental Planning and Management*, 59(12), 2251–2271. <https://doi.org/10.1080/09640568.2016.1140023>
- Southworth, J., & Tucker, C. (2001). The influence of accessibility, local institutions, and socioeconomic factors on forest cover change in the mountains of western Honduras. *Mountain Research and Development*, 21(3), 276–283. [https://doi.org/10.1659/0276-4741\(2001\)021\[0276:TIOALI\]2.0.CO;2](https://doi.org/10.1659/0276-4741(2001)021[0276:TIOALI]2.0.CO;2)
- Steiniger, S., & Hay, G. J. (2009). Free and open source geographic information tools for landscape ecology. *Ecological Informatics*, 4(4), 183–195. <https://doi.org/10.1016/j.ecoinf.2009.07.004>
- Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., & Ciolli, M. (2012). A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. *Environmental Modelling & Software*, 38, 203–213. <https://doi.org/10.1016/j.envsoft.2012.05.016>
- Zar, J. H. (2010). *Biostatistical analysis*, Fifth ed. Upper Saddle River, NJ.
- Zeng, H., Talkkari, A., Peltola, H., & Kellomäki, S. (2007). A GIS-based decision support system for risk assessment of wind damage in forest management. *Environmental Modelling and Software*, 22(9), 1240–1249. <https://doi.org/10.1016/j.envsoft.2006.07.002>