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Road network designing in a forested watershed using network connectivity indices

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Abstract: Designing and constructing a road network is one of the most critical steps of the development process in managing natural resources. The current research is going to investigate the application of network connectivity indices to the analysis of road networks in the forested watershed. First, the road network suitability map (RNSM) was created to emphasize the technical and physiographic criteria and integrated management scenarios using a weighted linear combination (WLC) and analytic network process (ANP). Subsequently, three road network alternatives (RNA) were assigned based on the priorities in the RNSM. In order to try to determine the appropriate alternative, the network connectivity of the designed alternatives looked into the forest and non-forest land uses, as well as the whole study area, using the values of alpha (α), beta (β), gamma (γ), eta (η), network density (*ND*) and detour indices (*DI*) in the context of the graph theory. Results show that the road density of the RNA2 variant (11.56 $m \cdot ha^{-1}$) is shorter than the other alternatives and the existing road network (ERN). In addition, dealing with the whole study area, we realized that the index values which are related to the number two reflect a better status than the other alternatives of alpha, beta, gamma, eta and detour index, in which they were identified to be 0.44, 1.34, 1.16, 0.45 and 0.83, respectively. RNA2 is chosen as the appropriate road network according to the network connectivity, technical and physiographical criteria, along with integrated management scenarios. Further control measures and field surveys are recommended to achieve more relevant results.

Keywords: graph theory; indexes; network alternative; road network suitability map (RNAM)

In a mountainous forested watershed, forest roads appear to be the leading infrastructure in order to implement the forest management processes, including timber harvesting, tree thinning and planting, along with wildlife and wildfire managing, protecting, and maintaining the forest area (Zhao et al. 2021). Forest roads could significantly alter the landscape of mountainous watersheds (Ramos-Scharrón et al. 2022). Despite all the detrimental effects which forest roads might have on the forest

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and other catchment ecosystems, their design and construction need to connect the land uses and access to the forest area (Akay et al. 2020).

The network consists of nodes or vertices linked together by edges where vertices are fundamental physical constructs and occupy particular positions in space and edges, e.g. roads or railway lines in transportation networks (Gastner, Newman 2006). Generally, road network structures set off both topologic and geometric characteristics (Sreelekha et al. 2016). The connectivity measures among the various indices which are adopted for evaluating road network properties could be referred to by several kinds of research. These measures assess the connection intensity between road segments. A large number of connectivity assessment indices exist to attempt to evaluate the connectivity pattern of the road network, including alpha (α), beta (β), gamma (γ), eta (η), network density, and detour indices (Al-dami 2015).

Previously, connectivity assessment indices have been extensively applied in road network connectivity, including studies such as by Levinson and Huang (2012), Olawale and Adesina, (2013), and Patarasuk (2013), who developed a GIS-based methodology for graph-based approaches (e.g. Loro et al. 2015; Ayo-Odifiri et al. 2017; Abbas, Hashidu 2019; Sarkar et al. 2020).

The road network in the Hyrcanian forests was generally designed on the basis of bottom-up mechanisms to aim at a forestry plan (Hosseini et al. 2012; Jourgholami et al. 2012), most frequently ignoring the fact that the forestry plan is a component of the watershed. Moreover, a public road was typically constructed in order to create a connection between villages and cities, fully disregarding the designing according to watershed management and other land use accesses in the watershed. The road network is the main forest watershed component, even though this point was ignored in most cases in forest road planning. Previous experience with this type of studies (Pentek et al. 2005; Abdi et al. 2009; Hosseini et al. 2012; Hayati et al. 2013) analysed and designed an appropriate road network to create the connections in forestry plan. Nevertheless, in the same way, there is barely any investigation into the forest road network evaluation in the watershed area.

The present study highlights to draw on the graph theory in order to analyse the existing road network and its temporal changes. Furthermore, it has dealt with analysing the existing road network (ERN) in which the new options have been designed according to the technical and physiographical criteria as well as the integrated management scenarios. Subsequently, the new alternatives were analysed by the use of the network connectivity indices, with the aim that the new approach would take into account various features.

The research would serve some purposes such as to: (*i*) evaluate current network connectivity using graph indices; (*ii*) create a suitability map in order to plan a new road network; (*iii*) design the road network alternatives to the study area considering the suitability map; (*iv*) assess the designed road network connectivity applying graph indices and finally to determine the appropriate road network for Chehel-Chai forest watershed.

MATERIAL AND METHODS

Research location

This study tried to focus the attention on the Chehel-Chay watershed, Minoodasht County, in Golestan Province, Northeast Iran. This area has extended between 36°59'N and 36°17'N latitude and 55°22'E and 55°37'E longitude (Figure 1). The Chehel-Chay watershed is about 25 680 ha and includes 30 villages with the population of almost 14 068. The elevation ranges from 190 m a.s.l. to 2 750 m a.s.l., and the mean annual rainfall is about 750 mm. The northern part is covered by forest areas, while in the southern part the forest is mixed with rangelands. The Chehel-Chay watershed territory is surrounded by forest (67%), cropland (28.8%), rangeland (4.09%), and villages (0.053%).

Methodology

Road network suitability mapping. Designing and construction of forest roads are affected by the extensive range of influencing factors to include topological, climatic, demographical, landscape, land use, and vegetation ones (Akay et al. 2020). Although the assessment of scenarios in decision-making tends to be highly critical, there has not been yet any standard practice in the forest road network in connection with the watershed boundary. An initiative aimed to fill this gap can be the efficient use of decision-making as a strong ally. In the current research, the Delphi technique was applied to determine essential criteria for road network planning according to integrated watershed management. There were nine forest engineering experts and also nine watershed management experts

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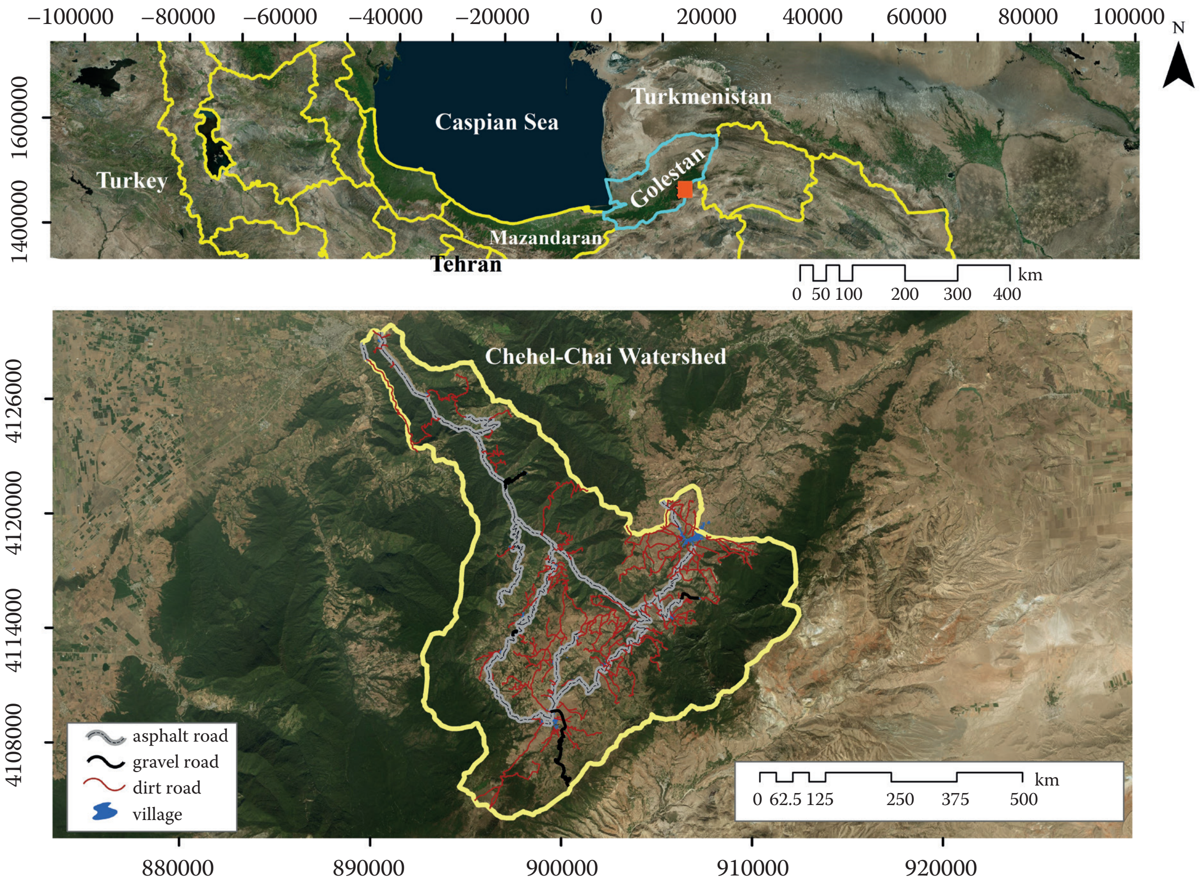

Figure 1. Location of the Chehel-Chai watershed in Iran and Golestan province

who were asked to fill in a questionnaire about the Delphi process. The process was performed in three rounds (Table 1). After each round, all responses were analysed, and the relative importance of each suggested criterion was calculated. At the conclusion, the criteria that could reach the third round were selected to produce the road network suitability mapping.

Quantification of the final criteria weights in analytic network process (ANP). The ANP method consists of two major steps; the first one implements pairwise comparisons for each of the dependency relationships to produce the relative major weights. In the second phase, the supermatrix calculation is generally split into three minor sections: the formation of the supermatrix, the normalization of the supermatrix, and the convergence to the solution (Tsai, Hung 2009). We used the ANP method in order to estimate the relative weights of selected criteria and sub-criteria. The response criteria represent their relative importance in the road network looking at the forest watershed accessibility. Then, we opted for the Super Decision Software (Version 3.2, 2019) to calculate the relative weight.

Data acquisition. In order to plan a new road network following the creation of the suitability map, we have sought to identify the fundamental criteria for putting the Delphi technique in three rounds to use (Table 2).

Physiographic data were drawn from the National Cartography Center, while geology and soil data were obtained from the Geological Survey and Mineral Exploration. Moreover, vegetation, natural and artificial distance, along with land cover data were extracted from different sources which were made available by the Secretariat of Integrated Management of the Chehel-Chay Watershed. In the following, slope and aspect layer were selected as physiographic variables, besides, the soil texture, soil and rock erodibility were performed in Geology and Soil Criteria categories. In the same way, the variable layers consisted of the distance to the residential area, the water resources, the connection point with the adjacent watershed, the location with fire occurrence, the landslide location, the fault, and electricity and the gas line were put in the title of natural and artificial dis-

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Table 1. The criteria categories in the Delphi approach

Criteria category	Round 1	Round 2	Round 3
Physiographic	slope	slope	slope
	aspect	aspect	aspect
	slope length	slope length	–
	elevation	–	–
Geology and soil	soil texture	soil texture	soil texture
	soil depth	soil depth	–
	soil drainage	–	–
	soil erodibility	soil erodibility	soil erodibility
	rock erodibility	rock erodibility	rock erodibility
Vegetation	forest type	forest type	forest type
	forest production capacity	forest production capacity	forest production capacity
	farmland	farmland	farmland
	excluded rangeland	excluded rangeland	excluded rangeland
	rangeland production capacity	–	–
Natural and artificial distance	distance to residential area	distance to residential area	distance to residential area
	distance to industrial area	–	–
	distance to recreational spot	distance to recreational spot	–
	distance to water resources	distance to water resources	distance to water resources
	distance to connection point with the neighbour watershed	distance to connection point with the neighbour watershed	distance to connection point with the neighbour watershed
	distance to occurred fire location	distance to occurred fire location	distance to occurred fire location
	distance to landslide location	distance to landslide location	distance to landslide location
	distance to fault	distance to fault	distance to fault
	distance to flood prone areas	distance to flood prone areas	–
	distance to ancient places	distance to ancient places	–
	distance to biological resources area	–	–
	distance to livestock, poultry, fisheries	distance to livestock, poultry, fisheries	–
	distance to electricity and gas line	distance to electricity and gas line	distance to electricity and gas line
Land cover	terracing	terracing	residential
	orchard	orchard	production forest
	agro-forestry	agro-forestry	agro-forestry
	conservation	conservation	orchard
	production forest	production forest	culture
	culture	culture	terracing
	tourist area	tourist area	conservative area
	residential	residential	tourist area

tance. At that moment, the land cover was divided into eight categories, including terracing, orchard, agro-forestry, conservation area, production and culture forest, tourism, and residential area. Lastly, all of the variable layers were created by geographic information system (GIS) tools (QGIS and ESRI ArcMap). The bar chart in Figure 2 marks the trends of the current research.

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Table 2. Selected variables used for suitability road network mapping

Criteria category	Input	Data	Source
Physiographic	slope aspect	raster / 10 m	National Cartography Center (NCC)
Geology and soil	soil texture soil erodibility rock erodibility	vector / 1 : 25 000 vector / 1 : 25 000 vector / 1 : 100 000	Geological Survey &Mineral Exploration (GSME)
Vegetation	forest type forest production capacity farmland	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image
Natural and artificial distance	distance to residential area distance to water resources distance to connection point with the neighbour watershed distance to occurred fire location distance to landslide location distance to fault distance to electricity and gas line	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image; 5 – Geological Survey & Mineral Exploration (GSME)
Landcover	terracing orchard agro-forestry conservation production forest culture tourist area residential	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image; 5 – Land Affairs Organization (LAO)

Criteria standardized using fuzzy logic approach. The criteria map was prepared in GIS and then converted to a raster format. Then this layer was standardized by the fuzzy function to a byte-level range of 0–255 (0 as the least and 255 as the maximum suitability rate at each criterion) in IDRISI software (Version IDRISI TerrSet, 2020). Among the available options to choose from, whereas the linear membership functions were found fit to represent a scenario to create road network suitability map (RNSM) and include triangular or trapezoidal shapes (Lyimo et al. 2020), then we opted for the linear membership functions. Finally, the produced RNSM was categorized into four categories (high, medium, weak, and very weak) according to the road planning aims and the current limitation (Figure 2).

Designing of the road network. Traditional methods for designing a forest road system used to be heavily reliant on an aerial photo interpretation and extensive fieldwork. Similarly, forest engineers have taken the large-scale contour layers on as the preliminary ways with dividers are known as route projection or 'pegging' (Abdi et al. 2009). The traditional techniques tend to be time- and cost-consuming, in which they evidently come across as simultaneously impossible to get the various affecting layers considered in road designing. In order to strike a balance on the particular downside, we draw on the PEGGER extension in ArcView software (2005).

Graph theory indices

The Network Analyst tool in GIS was run to determine the nodes and edges with the purpose to apply the graph theory. During the use of the graph theory, several network indices are applied to evaluate the accessibility and performance of the network analysis (Dinda et al. 2018). In the present study, alpha (α), beta (β), gamma (γ), eta (η), network density, and detour indices were used in or-

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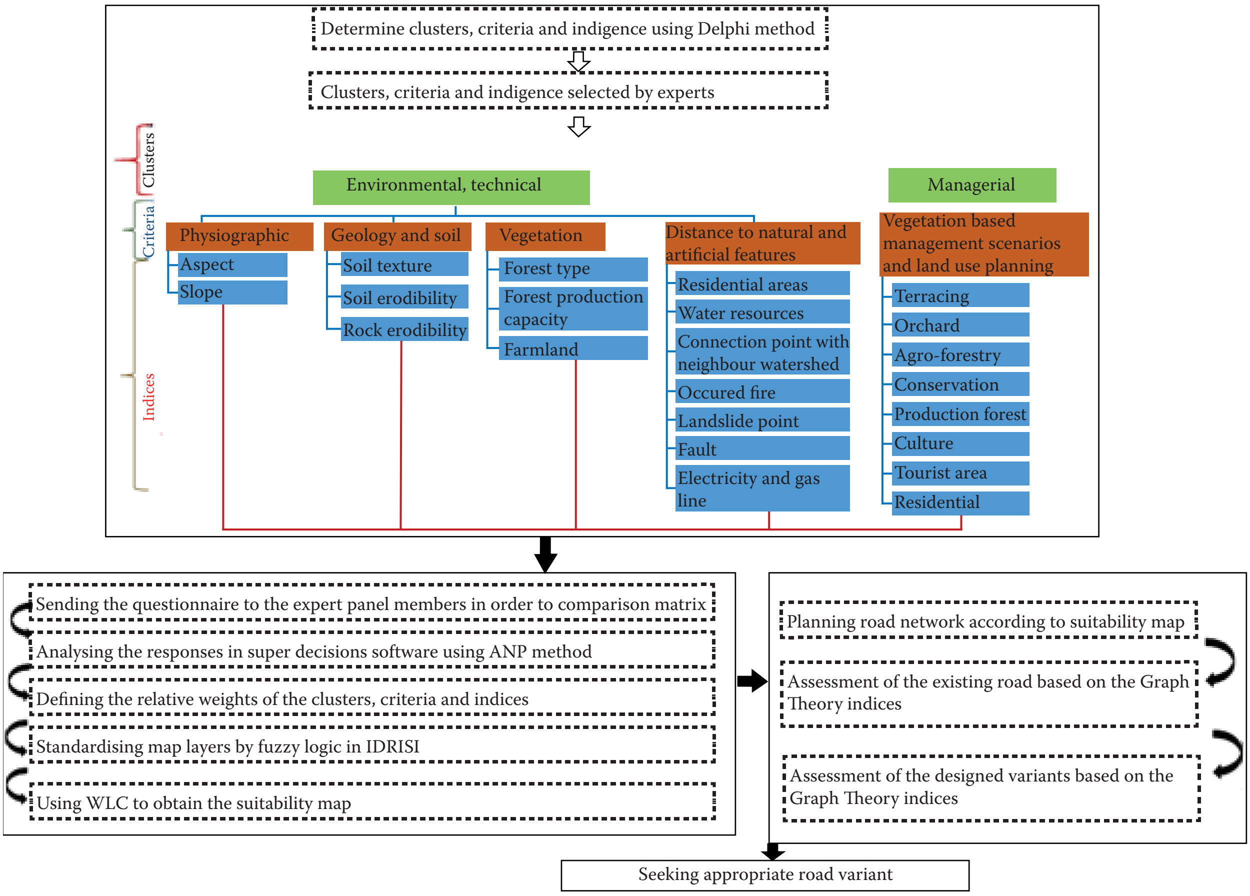

Figure 2. Flowchart of the implemented methodology of the Chehel-Chai watershed

ANP – analytic network process; WLC – weighted linear combination

der to evaluate the existing road network and road network alternatives (RNA) that was designed according to RNSM.

Alpha index (α). The alpha index highlights the ratio between the observed numbers of cycles in a graph in comparison with the maximum number of cycles. For completing the interconnected networks, the index will equal 1, whereas the trees and simple networks will have a value of 0 (Al-dami 2015; Sreelekha et al. 2016). Equation (1):

$$\alpha = \frac{e - v + p}{2v - 5} \quad (1)$$

where:
- α – alpha index;
- e – number of edges (links/routes);
- v – number of vertices (nodes);
- p – number of subgraphs in the network.

Beta index (β). The beta index (β) shows the level of connectivity in a graph and is expressed by the link between the number of edges over the number of vertices, as it shows the complexity and the completeness of the network (Rodrigue et al. 2009; Patarasuk 2013). Equation (2):

$$\beta = \frac{e}{v} \quad (2)$$

where:
- β – beta index.

Gamma index (γ). The gamma index (γ) is a measure of connectivity that considers the relationship between the number of observed links and the number of possible links (Rodrigue et al. 2009). Equation (3):

$$\gamma = \frac{e}{3 \times (v - 2)} \quad (3)$$

where:
- γ – gamma index.

Eta index (η). The eta index (η) measures the average edge length in the network and is used as the traffic network speed index, the summation

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and number of edges in the network need to measure the eta index (Nagne et al. 2013; Sreelekha et al. 2016). Equation (4):

$$\eta = \frac{L(G)}{e} \tag{4}$$

where:

η – eta index;

$L(G)$ – summation of all edges in the network (km);

e – number of edges in the network.

Network density (ND). Road network density is a factor which is to measure the road network development (Nagne et al. 2013). Equation (5):

$$ND = \frac{L}{A} \tag{5}$$

where:

ND – network density;

L – length of road network (m);

A – area (ha).

Detour index (DI). The detour index (DI) represents the efficiency of the road network connection and also marks the importance of physical situation for the route selection (Arienti et al. 2009). Equation (6):

$$DI = \frac{D}{I} \tag{6}$$

where:

DI – detour index;

D – straight distance;

I – ground distance.

RESULTS AND DISCUSSION

The watershed consists of two major components, water and land, whose surface and underground waters from rain and melting snow flow into a body of water such as a river, lake or reservoir. (Edwards et al. 2015). Therefore, the transport sector is one of the most important manmade infrastructures inside the watershed area (Reggiani et al. 2011).

Road network suitability map and variable importance

The variables were weighted by ANP, followed by carrying out the road network suitability map. According to the calculated relative weight among the clusters, the weight of the environmental and technical cluster (0.67) was higher than that of the managerial cluster (0.33). In comparison with the other physiographic criteria, it figured the most importance with a value of 0.54, followed by the geology and soil ones, the distance to the natural and artificial features and the vegetation with values of 0.26, 0.14 and 0.06, respectively (Table 3).

The residential index showed the highest value with a relative weight of 0.3 among land cover criteria, followed by the productive forest, agroforestry, orchard, culture, terracing, conservative forest, and tourist area with values of 0.2, 0.13, 0.1, 0.1, 0.07, 0.06 and 0.04, respectively.

The fuzzy map layers of the criteria were combined considering their weights. Then the suitability map was generated and classified into four categories (Figure 3). The results indicated that 36.13% of the study area was classified as the weak suitability category, followed by the very weak suitability category (32.59%), medium suitability category (29.58%) and high suitability category (1.69%) (Figure 3, Table 4).

Existing road network analysis

The investigation finding confirmed that the dirt roads have the highest length and density (243.54 km, 9.47 m·ha^{-1}) (Table 5).

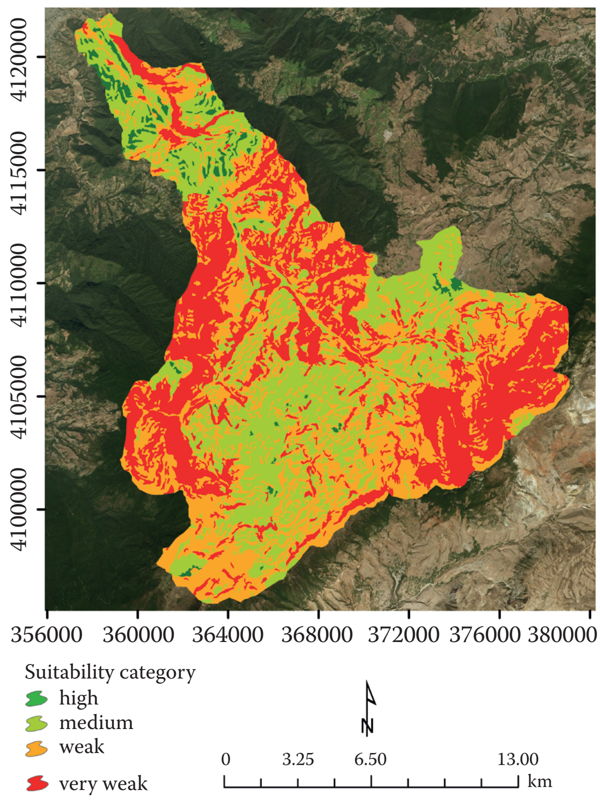

Figure 3. The road network suitability map of the Chehel-Chai watershed

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Table 3. The Analytic Network Process normalized supermatrix for competitive advantage of for road network suitability map of the Chehel-Chay watershed

Cluster	Weight	Criteria	Weight	Indices	Weight
Environmental and technical cluster	0.67	physiographic map	0.54	slope	0.89
				aspect	0.11
		geology and soil	0.26	soil erodibility	0.60
				rock erodibility	0.30
				soil texture	0.10
		vegetation	0.06	forest production capacity	0.72
				farmland	0.19
				forest type	0.09
		distance to natural and artificial features	0.14	distance to landslide point	0.22
				distance to residential area	0.19
				distance to water resources	0.16
				distance to fault	0.14
				distance to electricity and gas line	0.13
				distance to occurred fire location	0.12
				distance to connection point with the neighbour watershed	0.04
Managerial cluster	0.33	vegetation based management scenarios and land use planning	–	residential	0.30
				production forest	0.20
				agro-forestry	0.13
				orchard	0.10
				culture	0.10
				terracing	0.07
				conservative area	0.06
				tourist area	0.04

On the subject of the road network suitability categories, the highest length of existing roads was located in the medium suitability category. After that, the most significant density goes to the dirt roads (17.32 m·ha^{-1}), followed by the asphalt (4.61 m·ha^{-1}) and gravel roads (0.56 m·ha^{-1}). The largest road density in the high suitability category belonged to the dirt roads (8.28 m·ha^{-1}), then to the asphalt roads and the gravel roads with the density of (4.45 m·ha^{-1}) and (0.04 m·ha^{-1}), respectively.

Table 4. Road network suitability map categories area of the Chehel-chay watershed

Suitability category	Area (ha)	Percent of total area
High	435.13	1.69
Medium	7 595.89	29.58
Weak	9 278.86	36.13
Very weak	8 370.12	32.59

In the weak suitability category, the road density – from the most to the least – belongs to the dirt (8.86 m·ha^{-1}), the asphalt (3.42 m·ha^{-1}), and the gravel roads (0.61 m·ha^{-1}). The highest density in the very weak suitability category belongs to the dirt roads (3.09 m·ha^{-1}) (Table 6).

The results indicated that the alpha index values were 0.79, 0.14 and –0. 21 for the forest, non-forest land use and the whole study area, respectively. The calculated beta figures for the forest, non-forest land use and the whole study area were 0.4, 0.78 and 0.56, in turn. The eta figures were 1.2 (the forest area), 0.64 (the non-forest area), and 1.32 (the whole study area). Our results mark that the gamma index is 0.37, 0.19 and 0.27 for the forest, non-forest land use and the whole study area, respectively.

The network density figure for the non-forest land use (27.53 m·ha^{-1}) was the highest, followed by the figure which belonged to the whole study area (13.12 m·ha^{-1}), and the forest land use (6.17 m·ha^{-1}).

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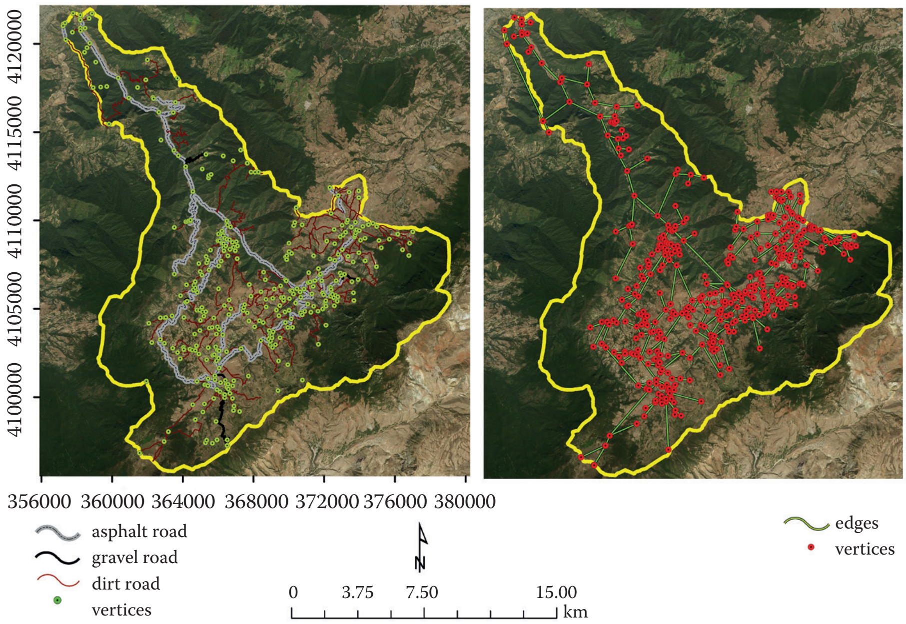

Figure 4. (A) Existing road network, (B) edges and vertices of existing road network of the Chehel-Chay watershed

In addition, the detour index was obtained for the forest, and the non-forest area, and the whole study area, i.e. 0.68, 0.81 and 0.71, in turn (Table 7).

The findings illustrated that network connectivity is relatively suitable for the forest area, however in the non-forest area despite an increase in the network density, the links between vertices (nodes) appear not to be reasonably appropriate. Therefore, the network connectivity ended up in an infirm position. The network density in the forest area came out inadequate, and in the non-forest area, the network connectivity has decreased despite the increasing network density. In addition, on the whole of the study area, the network predicted speed kept a low amount out of the topographic status along with the network development inadequate level.

Table 5. Existing road network and road network alternatives length and density of the Chehel-Chay watershed

Surface type	Road	Length (km)	Density (m·ha^{-1})
Asphalt	existing road network	82.87	3.23
Gravel		10.66	0.42
Dirt		243.54	9.47
Total		337.07	13.12
Asphalt	road network alternative 1	83.96	3.26
Gravel		10.65	0.41
Dirt		238.71	9.29
Total		333.32	12.97
Asphalt	road network alternative 2	77.85	3.03
Gravel		6.60	0.25
Dirt		212.85	8.28
Total		297.30	11.56
Asphalt	road network alternative 3	79.81	3.10
Gravel		19.48	0.75
Dirt		230.62	8.98
Total		329.91	12.83

Road network alternatives assessment

Three road network alternatives were designed based on the suitability map to the study area. Then the variants were evaluated concerning to RNSM and Graph Theory indices.

Road network alternative 1. The results indicated that in RNA 1, the dirt roads marked the highest length and density (238.71 km, 9.29 m·ha^{-1}), followed by the asphalt roads (83.96 km, 3.26 m·ha^{-1}) and the gravel roads (10.56 km, 0.41 m·ha^{-1}) (Table 5).

The road density of RNA1 was extracted from the suitability map. The findings point out that the most extensive road density in high suitability category belongs to the dirt roads (6.77 m·ha^{-1}), then to asphalt roads (0.2 m·ha^{-1}). The study got a mention that there were no gravel roads in such a category. In the medium suitability category, dirt, asphalt and gravel road density revealed 17.32 m·ha^{-1}, 4.62 m·ha^{-1}, and 0.57 m·ha^{-1}, in turn. The largest road density in the weak suitability category was in dirt roads (8.79 m·ha^{-1}), followed by asphalt roads (3.42 m·ha^{-1}), and gravel roads (0.6 m·ha^{-1}).

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Table 6. Detailed length and density of existing road network and road network alternatives on road network suitability map of the Chehel-Chay watershed

Road	Surface type	Suitability category	Length (km)	Density ($m \cdot ha^{-1}$)	% total roads
Existing road network	asphalt	HSC	1.94	4.45	0.58
		MSC	35.04	4.61	10.40
		WSC	31.76	3.42	9.42
		VWSC	14.14	1.68	4.19
	gravel	HSC	0.02	0.04	0.01
		MSC	4.27	0.56	1.27
		WSC	5.65	0.61	1.68
		VWSC	0.71	0.08	0.21
	dirt	HSC	3.84	8.28	1.14
		MSC	131.60	17.32	39.04
		WSC	82.21	8.86	24.39
		VWSC	25.9	3.09	7.68
Road network alternative 1	asphalt	HSC	2.95	6.77	0.89
		MSC	35.12	4.62	10.51
		WSC	31.76	3.42	9.53
		VWSC	14.13	1.68	4.24
	gravel	HSC	0	0	0
		MSC	4.39	0.57	1.31
		WSC	5.56	0.60	1.70
		VWSC	0.70	0.08	0.21
	dirt	HSC	10.34	0.02	3.10
		MSC	130.93	17.32	39.29
		WSC	81.64	8.79	24.49
		VWSC	15.80	1.88	4.74
Road network alternative 2	asphalt	HSC	1.45	1.86	0.49
		MSC	35.95	4.73	12.09
		WSC	31.00	3.34	10.43
		VWSC	9.45	1.13	3.18
	gravel	HSC	0	0	0
		MSC	2.88	0.37	0.97
		WSC	3.46	0.37	1.16
		VWSC	0.25	0.03	0.08
	dirt	HSC	6.38	3.00	2.15
		MSC	119.31	15.70	40.13
		WSC	73.15	7.88	24.60
		VWSC	14.01	1.67	4.71

Table 6. to be continued

Road	Surface type	Suitability category	Length (km)	Density ($m \cdot ha^{-1}$)	% total roads
Road network alternative 3	asphalt	HSC	3.64	8.37	1.11
		MSC	34.72	4.57	10.52
		WSC	26.93	2.90	8.16
		VWSC	14.52	1.73	4.41
	gravel	HSC	0.15	0.34	0.05
		MSC	8.20	1.08	2.49
		WSC	8.62	0.93	2.61
		VWSC	2.51	0.30	0.76
	dirt	HSC	15.67	36.01	4.48
		MSC	96.27	12.67	18.29
		WSC	83.95	9.05	25.45
		VWSC	34.73	4.15	10.55

HSC – high suitability category; MSC – medium suitability category; WSC – weak suitability category; VWSC – very weak suitability category

In the very weak suitability category, the highest road density is related to dirt roads (1.88 $m \cdot ha^{-1}$), asphalt roads (1.68 $m \cdot ha^{-1}$) and then gravel roads (0.08 $m \cdot ha^{-1}$) (Table 6).

According to the RNA1 assessment based on Graph Theory indices, alpha values demonstrate the figure of 0.81, 0.45 and 0.31 for the forest, non-forest land use and the whole study area, respectively. The beta values marked 1.58, 1.22 and 1.1 for the forest, non-forest land use and the whole study area. Research findings revealed that in the three sections of the forest, non-forest land use and the whole study area, the eta index was 1.4, 0.54 and 0.78, resp. The results also showed that the respective gamma values were 0.37, 0.23 and 0.19 for the forest, non-forest land use and the whole study area. The calculated network density in the component of the forest, non-forest land use and the whole study area was 6.48 $m \cdot ha^{-1}$, 25.74 $m \cdot ha^{-1}$ and 12.97 $m \cdot ha^{-1}$, respectively. Finally, the measured detour index in the forest, non-forest land use and the whole study area 0.73, 0.72 and 0.74 (Table 7, Figure 5).

Road network alternative 2. According to the metric analysis RNA2, the length and density of the dirt roads were 212.85 km and 8.28 $m \cdot ha^{-1}$ in most cases, followed by the asphalt roads (77.85 km, 3.03 $m \cdot ha^{-1}$) and the gravel roads (6.6 km, 0.25 $m \cdot ha^{-1}$) (Table 5).

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Table 7. Existing road network and road network alternatives analyses using Graph Theory of the Chehel-Chay watershed

Road	Land use	α	β	η	γ	*ND* (m·ha^{-1})	*DI*
	forest	0.79	0.40	1.20	0.37	6.17	0.68
ERN	non-forest	0.14	0.78	0.64	0.23	27.53	0.81
	total study area	–0.21	0.56	1.32	0.19	13.12	0.77
	forest	0.81	1.58	1.40	0.40	6.81	0.73
RNA1	non-forest	0.41	1.22	0.54	0.41	25.74	0.72
	total study area	0.35	1.10	0.78	0.37	12.97	0.74
	forest	0.90	2.00	1.62	0.44	6.48	0.73
RNA2	non-forest	0.45	1.30	0.88	0.43	22.21	0.74
	total study area	0.44	1.34	1.16	0.45	11.56	0.83
	forest	0.86	1.45	1.12	0.33	10.54	0.73
RNA3	non-forest	0.44	1.31	0.95	0.44	21.76	0.69
	total study area	0.41	1.05	1.06	0.31	12.84	0.71

ERN – existing road network; RNA – road network alternatives; α – alpha; β – beta; η – eta; γ – gamma; *ND* – network density; *DI* – detour index

Concerning the suitability map, the largest road density of RNA2 in the high suitability category is related to dirt roads (3 m·ha^{-1}), while the second largest went for the asphalt roads (1.86 m·ha^{-1}). Concerning the medium suitability category, the dirt, asphalt and gravel road density obtained 15.7 m·ha^{-1}, 4.73 m·ha^{-1} and 0.37 m·ha^{-1}. In the weak suitability category, the largest road density belonged to dirt roads (7.78 m·ha^{-1}), then to asphalt roads (3.34 m·ha^{-1}) and gravel roads (0.37 m·ha^{-1}). The most significant road density was related to dirt roads (1.67 m·ha^{-1}) in the very weak suitability category. After that, there were asphalt (1.13 m·ha^{-1}), and gravel roads (0.03 m·ha^{-1}) (Table 6).

The investigation came across that the alpha value was 0.9, 0.45 and 0.44 in the forest, non-forest land use and the whole study area, respectively. In the following, we found that the beta value in the forest, non-forest land use and the whole study area

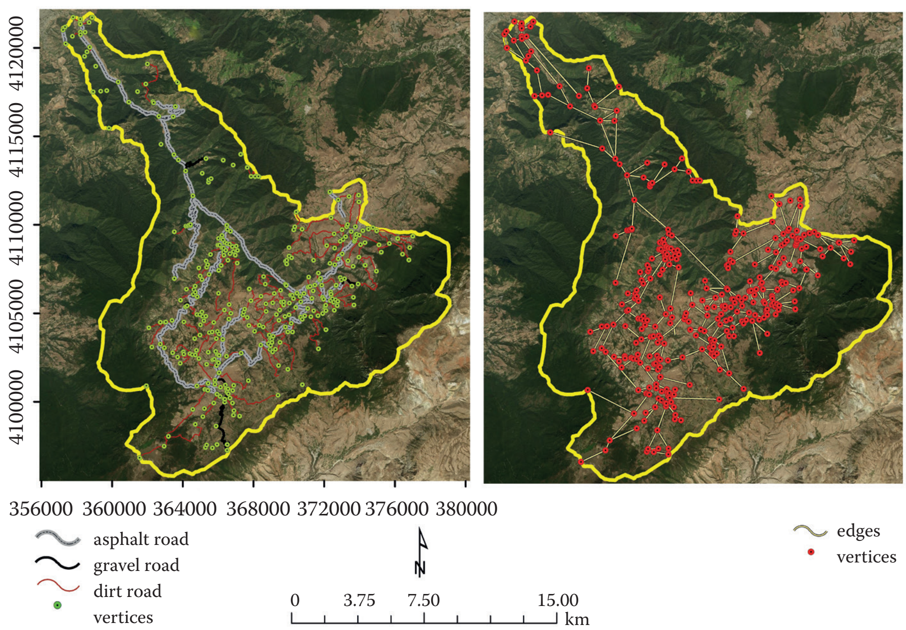

Figure 5. (A) Road network alternative 1, (B) edges and vertices of road network alternative 1 of the Chehel-Chay watershed

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was 2, 1.3 and 1.34, respectively. The respective eta values for the forest, non-forest land use and the whole study area revealed 1.4, 0.54 and 0.78. The results also indicated that the gamma rate was 0.44, 0.43 and 0.45 for the forest, non-forest land use and the whole study area respectively (Table 7, Figure 6).

Road network alternative 3. By carrying out the research, we found that in RNA3, the dirt roads featured the highest length and density (230.62 km, 8.98 m·ha^{-1}), followed by the asphalt roads (79.81 km, 3.1 m·ha^{-1}) and the gravel roads (19.48 km, 0.75 m·ha^{-1}) (Table 5).

The study results also showed that according to the RNSM analysis, the density of the dirt roads in the high suitability category was 36.01 m·ha^{-1}, followed by the asphalt and gravel roads (36.01 m·ha^{-1} and 0.34 m·ha^{-1}) along with the dirt roads with density of 13.67 m·ha^{-1} in the medium suitability category. Our findings revealed that in the weak suitability category, the highest road density was related to dirt roads (9.05 mh^{-1}), followed by asphalt roads (2.9 m·ha^{-1}) and gravel roads (0.93 m·ha^{-1}). Furthermore, in the very weak suitability category, the dirt road density was 4.15 m·ha^{-1}, followed by asphalt (1.73 m·ha^{-1}) and gravel roads (0.03 m·ha^{-1}) (Table 6).

As a result of the graph theory analyses, the alpha value appeared to be 0.86, 0.44 and 0.41 for the forest, non-forest land use and the whole study area, respectively. In the forest, non-forest land use and the whole study area the beta value obtained 1.45, 1.31 and 1.05, respectively. The eta index rate revealed 1.12, 0.95 and 1.06 in the forest, non-forest land cover and the whole study area, in turn. The research noted that the gamma value was 0.44, 0.43 and 0.45 in the forest, non-forest land use and the whole study area, respectively.

The network density index in the forest, non-forest land use and the whole study area was measured as 10.54 m·ha^{-1}, 21.76 m·ha^{-1} and 12.84 m·ha^{-1}, respectively. Ultimately, the detour index in the forest, non-forest land use and the whole study area appeared to be 0.73, 0.69 and 0.71, respectively (Table 7, Figure 7).

The structure or complexity of a road network is identified by the addition of a new linkage and expansion of the existing routes (Nagne et al. 2013). In addition, well-designed roads should be implemented according to the vulnerability of forest ecosystems along with the ecological and technical circumstances. The road construction impacts need to be carefully assessed in terms of physical, biological, economic, and social aspects from place to place. Our results indicated that a larger part of the existing road network has been located in the very weak suitability category, which means that the inherent limitations and technical standards have been remarkably ignored in road designing and construction. Hence, the lower road length was allocated to the very weak suitability category and the maximum amount went to the medium suitability category in RNA1 and RNA2

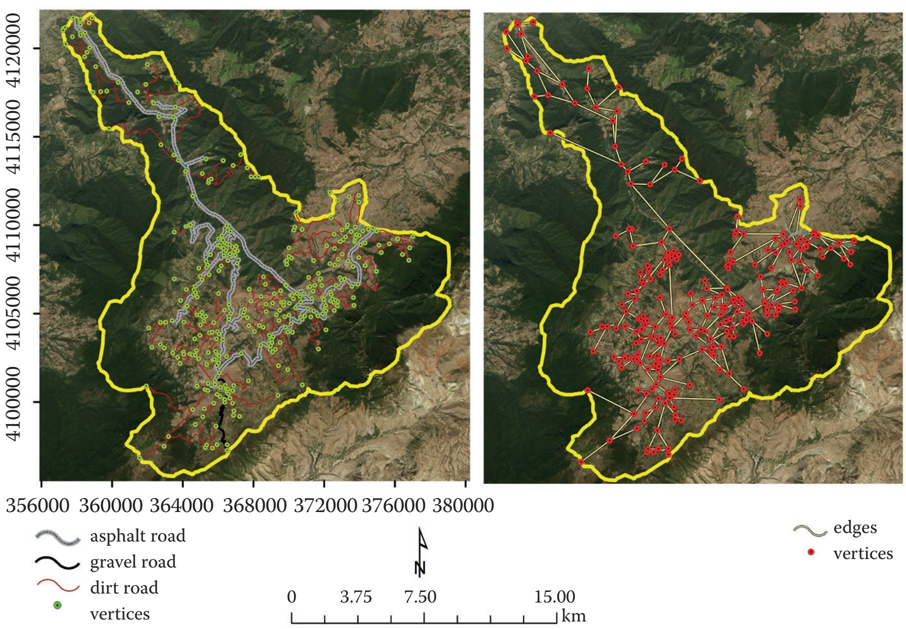

Figure 6. (A) Road network alternative 2, (B) edges and vertices of road network alternative 2 of the Chehel-Chay watershed

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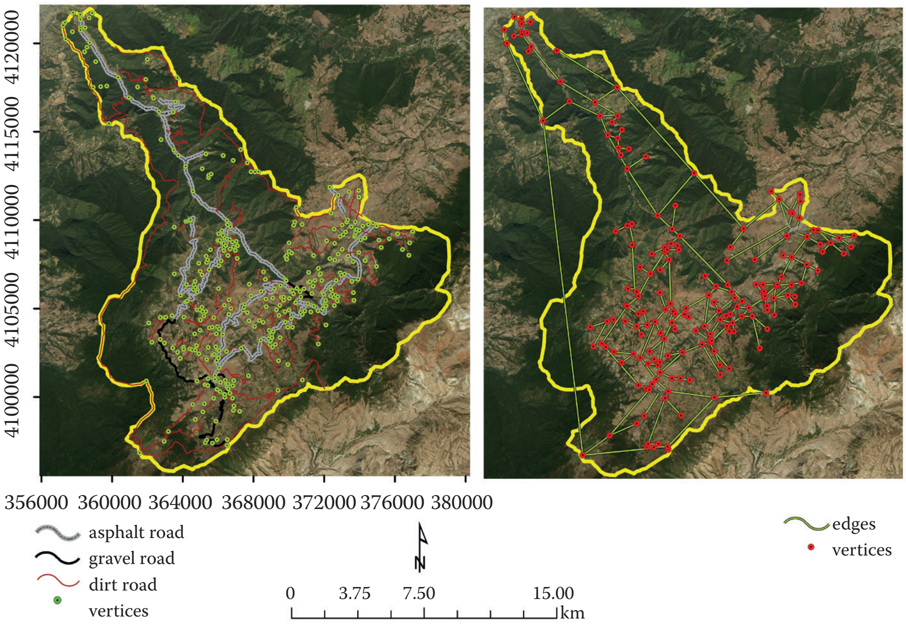

Figure 7. (A) Road network alternative 3, (B) edges and vertices of road network alternative 3 of the Chehel-Chay watershed

during the road network designing process. The described techniques in our findings can be employed to make the experience more valuable for decision-makers in which they would be able to take the multilateral vision in order to mitigate the plenty of road construction side-effects on the ecosystem.

When it comes to the findings, the majority of the existing road network was located in non-forest land use, even though 65% of the research area is covered by forest vegetation. Therefore, there has scarcely been a finely balanced approach in terms of allocating the road design in the forest area, meanwhile, in the non-forest area, a road overlap was observed. Subsequently, the existent inaccessible regions in the forest area lead to the forest management plan disruption such as forest conservation, reforestation, forest harvesting, and wildfire suppression. For this reason, the current and potential road locations and specifications must be pre-defined in the forest road network designing (Akay et al. 2013). In hope to be able to achieve a breakthrough, we designed the three Road Network Alternatives so that RNA2, with the lowest density, would massively cover the most of the study area, especially the forest land use.

The connectivity index serves to mark the accessibility nature of the study area and the land uses, not to mention the accessibility of any region is also determined by a well suited connectivity at that region (Sarkar et al. 2020). The graph theory indices took into account looking closely over the network structure of the study area. Going according to the road network analyses, the alpha index value was positive and higher than in the existing road network in all three designed alternatives while in the whole study area, this index came out negative. The results revealed the weak connectivity in the current existent road network as well as they supported the Al-dami (2015) findings. The alpha value of the road network in RNA2 was higher than in the other ones, as the recent facts have given the impression of more connectivity in this alternative than in the others. The beta value in RNA2 was pointed out as higher than in the other alternatives and the existing road network. The indices measure the level of connectivity in the network (Levinson, Huang 2012). The value of the beta index which is equal to zero is demonstrating the nodes without connecting, while the excellent value for the beta index is 2.5 (Al-dami 2015) and the value 1.4 is explaining the appropriate connectivity throughout the network (Levinson, Huang 2012). As a consequence of the beta index, RNA2 appeared more reasonable than the other alternatives which approved the acceptable connection between the nodes and vertexes. For the study area, the eta amount of the road network in RNA2 is marked higher than the appropriate RNA1, which is indicative of the average length per link, and it shows the network speed (Sreelekha et al. 2016). Therefore, in the light of the eta index, RNA2 figured as the quickest alternative compared to the two others. In view of the gamma

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value, RNA2 figured as the suited one, followed by RNA1 and RNA3. The value of the gamma index in all alternatives went more than in the existing network, which quantifies the progress of a network in time (Sreelekha et al. 2016). Accordingly, the connectivity between nodes in RNA2 appeared more preferable than in the other variants. Out of the findings, the highest value of the detour index belonged to variant two, which describes the efficient spatial level of the network and would be located in a value range between 0 and 1, which is rare if the network should possess the detour index of 1 (Levinson, Huang 2012). For this reason, RNA2 could be considered as quite an acceptable practical choice compared to the others. The variant two density appeared lower than in the other variants and the current road network, while the other indices of the graph theory for such an alternative went higher than in variant one and three as well as in the existing road network. Patarasuk (2013) indicated that an increase in the road density more probably could not thoroughly improve the graph theory indices, unlike in our research findings, in which the increasing connectivity in all alternatives began to improve in comparison with the existing road network. Thus, the recent finding appears to be in line with Sreelekha et al. (2016), who significantly recommended using the management factors along with the graph theory indices aimed at the road network assessment.

CONCLUSION

Carrying out this study lets us do the existing road network analysis accompanied by making use of new alternatives by applying plenty of network connectivity indices and the road network suitability map. The existing road network was assessed, which marked how such available road connectivity in the study area is not an acceptable way, particularly in forest land use. Although the forest vegetation has been covering more than half of the research area, the current road network has not been able to create a reasonable accessibility standard within the forest watershed. Consequently, it poses numerous obstacles to be overcome in conducting the forest management aims. For this reason, trying to practically implement a long-term road network plan with regard to the forestry approaches is in dire need. The main research findings demonstrate that in all the presented alternatives, the connectivity has distinctly been improved in comparison with the existing road network. In addition, it confirms the impression that the indices values which go in RNA2 featured higher than in RNA1 and RNA3, and in the existing road network. In the end, the study makes it clear that the road network connectivity indices have generally been applicable in order to attempt to analyse the road network in a forest watershed.

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The beneficial role of arbuscular mycorrhizal fungi on population rates of aboveground herbivory: *Zyginella pulchra* (Hemiptera, Cicadellidae) in plane trees

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Abstract: Herbivorous pests and arbuscular mycorrhizal fungi (AMF) coexist on the same host plant, having an indirect effect on one another. We established an experiment in a randomised complete block design with four treatments and six replications to examine the impact of AMF on the population and the damage caused to plane trees by the leafhopper *Zyginella pulchra*. Manure, manure plus fertiliser, manure plus fertiliser plus AMF, and non-inoculated plants (control) were all of the treatments. The findings revealed that while the nutritional content and soluble carbohydrate content were significantly enhanced by all treatments, they largely reached their peak in the AMF-inoculated plants. When compared to control trees that were not inoculated, the concentrations of N, P, and Zn were boosted by 39%, 81%, and 425%, respectively. AMF inoculation increased the population of *Z. pulchra* nymphs and adults compared to the control. However, the plants with AMF inoculation eventually suffered greater leaf loss as a result of this rise in the pest population. The findings show that while AMF enhance nutrient absorption and are necessary to improve the nutritional state of the host trees, they also enhance the absorption of pests that are thought to be harmful to plane trees. However, AMF colonisation improved the potential attractiveness of *Z. pulchra* to plane trees.

Keywords: insect attractiveness; leaf damage; mycorrhizae; nutritional status; *Platanus orientalis*

Various species of *Platanus orientalis* L., commonly known as plane trees, are distributed across diverse geographical regions and exhibit adaptability to varying climatic conditions. The plane tree is a sizable and aesthetically pleasing tree with a broad and far-reaching canopy. The aforementioned characteristics have established the plane tree as a significant tree within the surrounding environment, as noted by Sabeti (1976). *Zyginella pulchra* (Cicadellidae, Typhlocybineae) is considered to be a pest of plane trees due to its impact on their foliage. According to Wilson and Muhlethaler (2010), *Acer* species (*Acer* spp.) are the primary host plants of the pest; however, it has the potential to impact a diverse array of plants, including but not limited to plane trees, cypress (*Cupressus* spp.), and yew trees (*Taxus baccata*). The feeding behaviour of pests on almond (*Prunus dulcis* Mill. DA Webb), plum (*Prunus domestica* L.), peach (*Prunus persica* L.), and apple (*Malus domestica* L.) trees has been documented in various provinces of Iran. The pest nymphs and adults

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exhibit frequent activity on the underside of leaves, while the resulting injury symptoms, such as discoloured spots, are observable on the upper surface of leaves (Radjabi, Mirzayans 1989).

The literature suggests that plants have evolved various defence mechanisms in response to herbivorous threats, as evidenced by studies conducted by Agrawal (2007) and Rasmann and Agrawal (2009). These defensive features are believed to have arisen through selective pressures imposed by herbivores (Agrawal 2007; Züst, Agrawal 2016). Nevertheless, while plant traits play a crucial role in pest resistance, recent research has also highlighted the importance of inter-species communication, such as with arbuscular mycorrhizal fungi (AMF), in enhancing plant defences (Hartley, Gange 2009; Simon et al. 2017a).

The symbiotic relationship between arbuscular mycorrhizal fungi and plants has the potential to enhance the host plant ability to absorb water and nutrients, specifically phosphorus (P) and nitrogen (N), ultimately leading to an increase in plant growth (Smith, Read 2008; Treseder 2013; Garcia et al. 2016; Aalipour et al. 2020, 2021). The quality of host plants is a predominant factor influencing the performance of insect herbivores. Hence, it is predictable that the plants inoculated with AMF exhibit an impact on the preference and performance of insect herbivores, as reported by Ng et al. (2022). The influence of plant nitrogen and phosphorus contents on insect performance has been demonstrated in previous studies (Elser et al. 2000; Currie et al. 2011). The growth of herbivorous pests is influenced by the nutritional status of plants, as evidenced by studies conducted by Schmid-Hempel (2005), Lee et al. (2008), and Triggs and Knell (2012). AMF inoculation influences the quality of host plants (Frew et al. 2017). Insect performance is largely determined by the nutritional status of their host plants. Interactions between insects and host plants that are mediated by AMF can be advantageous for both the host plant and the parasite (Pineda et al. 2010). The impact of AMF on herbivores is characterised by a high degree of variability, ranging from positive to negative effects (Bennett, Bever 2007). Nevertheless, these interactions are contingent upon numerous variables. These relationships can be modified by environmental factors, such as the availability of nutrients for the host plant. As demonstrated by Frew et al. (2017), alterations in plant resistance to herbivores can be attributed to nutrient limitation. Furthermore, the colonisation of arbuscular mycorrhizal fungi (AMF) has the potential to enhance plant nutrition and improve the concentration of soluble sugars, thereby promoting the invasion of insects (Cardoza et al. 2003).

The impact of AMF on plant resistance to pest herbivores was studied by Vannette and Hunter (2011), which in turn can affect pest population parameters as demonstrated by Wooley and Paine (2007). However, the effects on the fitness of the parasite vary based on the species characteristics of the AMF, the host plant, and the herbivore (Gange 2007; Vannette, Hunter 2011). The impact of AMF colonisation on herbivores can vary in terms of its effects, as has been demonstrated in previous research (Shrivastava et al. 2015; Gange et al. 1999; Gehring, Bennett 2009). It has been found that such colonisation can be either detrimental, advantageous or have no discernible impact on these organisms. However, a comprehensive understanding of the ultimate impact of arbuscular mycorrhizal fungal (AMF) colonisation on the population density of insect pests on their host plants remains elusive. A comprehensive investigation of the mechanisms underlying the tripartite interactions is yet to be conducted, as stated by Koricheva et al. (2009).

The primary objective of this investigation was to assess the potential impact of arbuscular mycorrhizal fungal (AMF) colonisation on the population density of *Z. pulchra* and the extent of leaf damage in plane trees. The correlation between the nutrient content of plants and the population of insects was also examined. Two hypotheses were examined in this study: (*i*) does the colonisation of AMF have an impact on the attractiveness of plane trees to *Z. pulchra*? and (*ii*) does this pest exhibit a preference for plants that have been inoculated with AMF?

MATERIAL AND METHODS

Experimental site and treatments. The study was carried out between 2014 and 2015 at Isfahan University of Technology, located in Isfahan, Iran (32°39'N, 51°40'E; 1 600 m a.s.l.). The research was conducted on sandy-clay soil with pH of 7.5 and electrical conductivity (EC) of 2.48 $dS\cdot m^{-1}$. The location is characterised by its arid climate, frigid winters, average annual precipitation of 122.8 mm, and

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the average annual temperature of 23.4 °C. A total of 24 specimens of plane trees (*P. orientalis* L.) that were 15 years old and uniform in size were chosen.

Manure (M), manure + fertiliser [MF; water-soluble 20 : 5 : 10 N : P : K compound fertiliser with 12.8% sulphur, 1.3% magnesium oxide (NovaTec Solub, Compo, Germany)], manure + fertiliser + AMF (MFA), and non-inoculated plants (control) were the four treatments in this study. There were six replications of each treatment. We inoculated *Rhizophagus irregularis* and *Funneliformis mosseae* as mycorrhizal treatments. Control plants were not inoculated.

Two identical holes (measuring 0.5 m × 0.5 m) were filled with three different types of filling materials, based on the treatment applied. In order to perform mycorrhizal inoculation, 250 g (80 spores per g) of mycorrhizal inoculum (obtained from the National Soil and Water Research Center located in Karaj, Iran) were introduced into each individual hole. The trees were subjected to M and MF treatments, wherein they were provided with 5 kg and 0.1 kg of manure and fertiliser per hole, respectively. The control group did not receive any intervention and instead underwent a procedure in which two identical holes were drilled. The trees received weekly irrigation. Table 1 displays the properties of soil and cow manure.

Plant analysis. The standard technique of dry ashing was used to determine the mineral nutrients (N, P, K, Fe, and Zn) in leaves. Four different tree sides were adopted to randomly choose leaf samples. In brief, the 48-h oven drying at 65 °C produced dried leaves. P, K, Fe, and Zn were extracted from the samples using 2 M HCl following 550 °C, 5.5 h of dry ashing (Aalipour et al. 2019). K was determined using a flame photometer, whereas Fe and Zn were measured using atomic absorption spectrometers (AA-670; Shimadzu, Japan). Phosphorus was measured using a spectrophotometer (UV-600A) at 460 nm using the vanadomolybdophosphoric acid colorimetric method (Eaton et al. 1995). Total N was determined using the Kjeldahl technique (Eaton et al. 1995).

Evaluation of the insect population and leaf damage. Digital image processing with MATLAB software was employed to assess the extent of leaf damage caused by insects. To accomplish this task, a sample of 100 leaves was randomly chosen from each tree and subjected to scanning of both leaf surfaces using a Canon 4410 scanner (Canon, Japan). Subsequently, a set of colours was established within the software to represent the various types of damage imposed by insects on leaves. The data pertaining to the pixel and colour attributes of individual leaves were exported in the form of '.csv' files, which could then be imported into MATLAB (Version 8.4, 2014) software to facilitate the computation of damaged areas, as described by Rathod et al. (2013).

Evaluation of adults and nymphs. In order to assess the population of leafhopper adults and nymphs, a random selection of four twigs measuring 20 cm in length was obtained from the central region of the crown, taken from four different directions. These twigs were promptly transferred to the laboratory in plastic bags on ice. Subsequently, the branches underwent a washing process utilising a combination of water and detergent. Following this, sifting was conducted, and the total amount of both adult and nymph specimens was recorded per 50 leaves.

In this experiment, in addition to leaf injury caused by *Z. pulchra* feeding, leaf chlorosis was also observed, most likely due to a deficiency of micronutrients such as Fe and Zn.

Statistical analysis. The data obtained from *P. orientalis* L. was analysed using the randomised complete block design (RCBD) and subjected to analysis of variance (ANOVA) using SAS (Version 9.1, 2003) with six replications. The statistical analysis involved performing means comparisons through the implementation of the least significant difference (LSD) test at a significance level of 0.05. Statistical Pearson's correlation coefficient (*r*) was used to establish the relationships between variables through a statistical correlation analysis.

Table 1. Soil and manure physico-chemical properties

Factors	Texture	pH	*EC*	*OM*	N	P available	K exchangeable	Fe	Zn
			(dS·m^{-1})	(%)		(mg·kg^{-1})			
Soil	clay	7.90	1.53	1.15	0.15	140	235	1 400	21
Manure	–	8.02	15.23	20.40	3.07	791	2 030	12 300	194

EC – electrical conductivity; *OM* – organic matter

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Table 2. Comparison of 2-year means of nutrients concentration under AMF and other treatments in plane tree leaves

Year	Treatment	N	P	Fe	Zn
		(g·kg^{-1})		(mg·kg^{-1})	
2014	control	7.69 ± 0.28^{d}	11.10 ± 0.85^{e}	44.70 ± 2.90^{c}	4.90 ± 0.90^{e}
	manure	8.57 ± 0.30^{c}	13.40 ± 1.60^{d}	57.60 ± 2.80^{c}	12.20 ± 1.10^{d}
	manure + fertiliser	9.44 ± 0.36^{b}	14.10 ± 0.95^{cd}	55.80 ± 3.60^{c}	14.90 ± 1.70^{c}
	AMF	9.94 ± 0.38^{b}	15.90 ± 1.00^{c}	67.90 ± 2.00^{c}	24.60 ± 2.40^{a}
2015	control	7.26 ± 0.17^{d}	10.70 ± 0.69^{e}	65.20 ± 8.00^{c}	4.73 ± 0.89^{e}
	manure	9.73 ± 0.82^{b}	19.10 ± 3.00^{b}	236.00 ± 16.00^{b}	18.00 ± 2.30^{b}
	manure + fertiliser	9.87 ± 0.43^{b}	20.50 ± 2.10^{b}	242.00 ± 18.00^{ab}	19.60 ± 2.80^{b}
	AMF	10.80 ± 0.71^{a}	23.50 ± 2.60^{a}	272.00 ± 29.00^{a}	26.00 ± 2.20^{a}

$^{a–e}$ Means (± SD) followed by similar letters within each column do not express significant differences at $P < 0.05$ according to the LSD test; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

RESULTS AND DISCUSSION

A significant interaction impact of year × treatments on nutritional levels was found using the analysis of variance (data not shown). The concentrations of N, P, Fe, and Zn in the leaves of plane trees were increased in mycorrhizal plants (Table 2). When compared to control plants, AMF-inoculated plants significantly increased P (by 43% and 119%) and Zn (by 402% and 449%, respectively) in 2014 and 2015. Regardless of the nature of the combination, all treatments successfully increased the Fe and N concentrations in the leaves. Although N appeared to be more dependent on the composition of the mixture, Fe could be increased by adding any type of fertiliser (Table 2).

The treatments that received AMF inoculation exhibited the highest peak in soluble sugar content. The results indicate that AMF-inoculated plants exhibited a significant increase in soluble sugar content, with a respective increase of 31.1% and 40.6% in 2014 and 2015, as depicted in Figure 1, when compared to the control plants.

The treatments had a significant impact on the population of nymphs and adults, as depicted in Figures 2 and 3. The inoculation of trees with AMF resulted in a significant increase in the num-

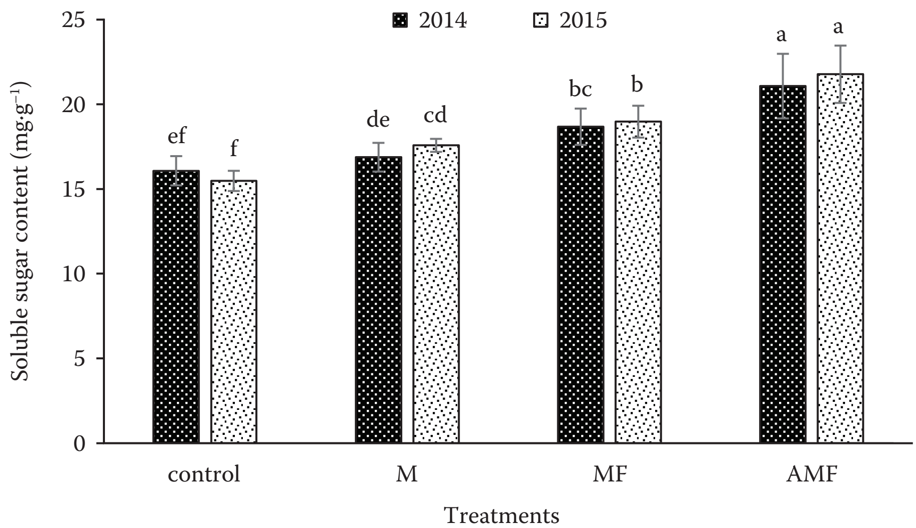

Figure 1. Influence of different treatments on soluble sugar content in plane tree

$^{a–f}$ Means followed by same letter do not differ significantly by LSD tests at $P \leq 0.05$; M – manure; MF – manure + fertiliser; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

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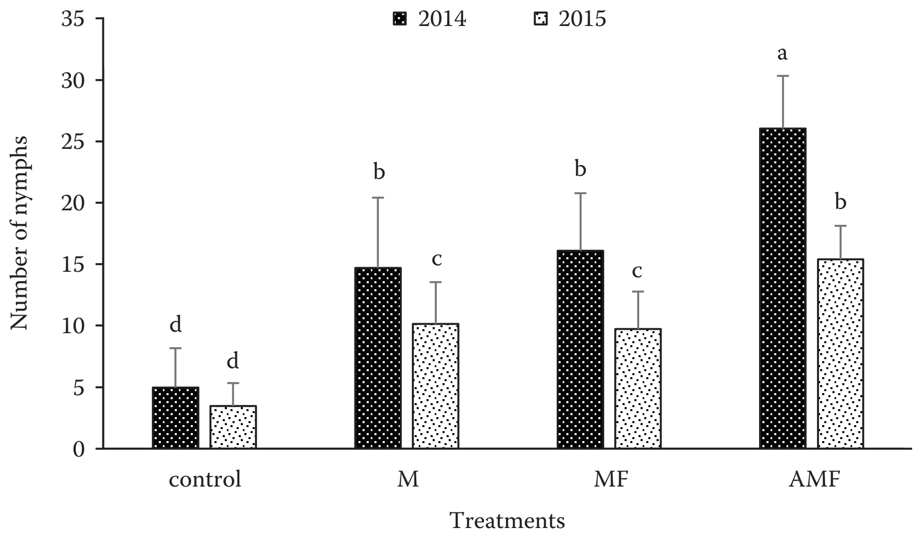

Figure 2. Influence of different treatments on the number of *Zyginella pulchra* nymphs in plane tree

[a–d] Means followed by same letter do not differ significantly by LSD tests at $P \leq 0.05$; M – manure; MF – manure + fertiliser; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

ber of nymphs and adults. Specifically, in 2014 and 2015, the number of nymphs increased by 424% and 342%, respectively, while the number of adults increased by 707% and 480%, respectively, when compared to control plants. The treatment with AMF also yielded the highest number of nymphs and adults recorded. Plants inoculated with AMF exhibited a significant increase in nymphs (62% and 58% for 2014 and 2015, respectively) and adults (72% and 90% for 2014 and 2015, respectively) compared to those that were solely treated with manure and fertiliser. The study revealed noteworthy associations between the number of nymphs and the elements N and Zn (r = 0.53 and 0.66, respectively, $P < 0.01$), as well as between the number of adults and N and Zn (r = 0.57 and 0.64 respectively, $P < 0.01$). The rise in the *Z. pulchra* population may be attributed to significant and consistent enhancements in the nutrient levels of the plant. The study revealed a significant and positive correlation between the quantity of soluble sugar and the count of adult and nymph insects, with correla-

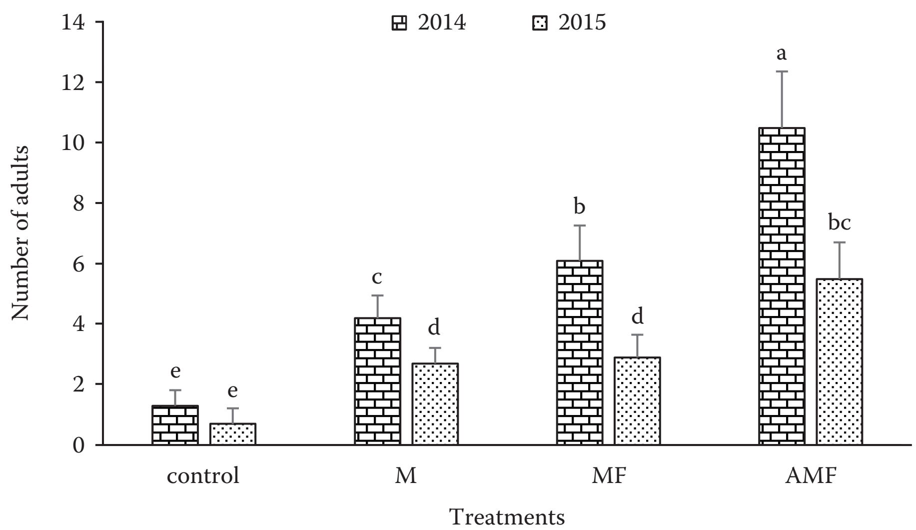

Figure 3. Influence of different treatments on the number of *Zyginella pulchra* adults in plane tree

[a–e] Means followed by same letter do not differ significantly by LSD tests at $P \leq 0.05$; M – manure; MF – manure + fertiliser; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

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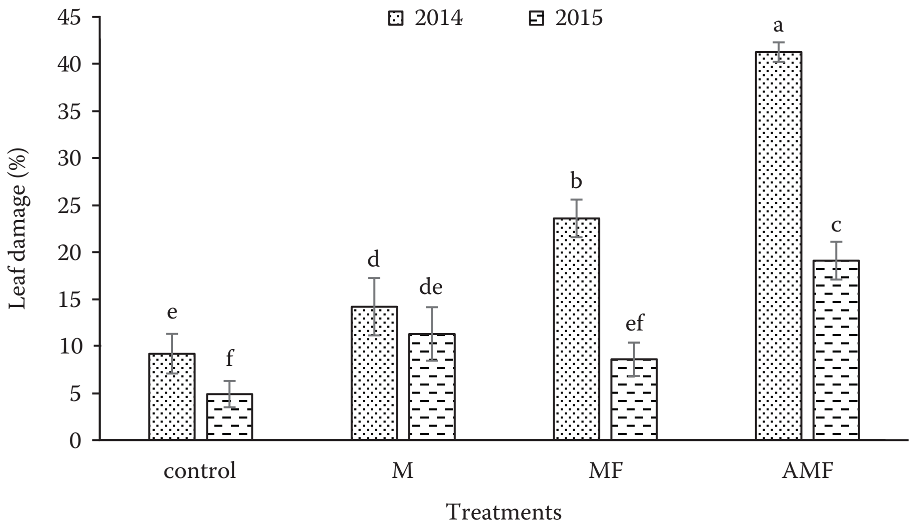

Figure 4. Influence of different treatments on leaf damage in plane tree.

[a–f] Means followed by same letter do not differ significantly by LSD tests at $P \leq 0.05$; M – manure; MF – manure + fertiliser; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

tion coefficients of 0.73 and 0.62, respectively, and a *P*-value of less than 0.01.

Based on the data, it was observed that the AMF-inoculated plants exhibited the highest percentage of leaf damage, while the control plants displayed the lowest amount of damage (Figure 4). The results indicate that leaf chlorosis showed a reverse trend, whereby the control group had the highest percentage of chlorosis, while the AMF-inoculated plants had the lowest percentage (Figure 5). There were negative correlations between leaf chlorosis and insect population ($r = -0.61$ and -0.64 for adults and nymphs, respectively, $P < 0.01$). An observation was made of a significant positive correlation between leaf damage and insect population, with correlation coefficients of 0.89 and 0.79 for adults and nymphs respectively, and a *P*-value of less than 0.01.

The presence of arbuscular mycorrhizal fungi can have both positive and negative impacts on the population of insect herbivores. Gehring and Bennett (2009) reported that the presence of AMF may not always have a consistent effect, and in certain

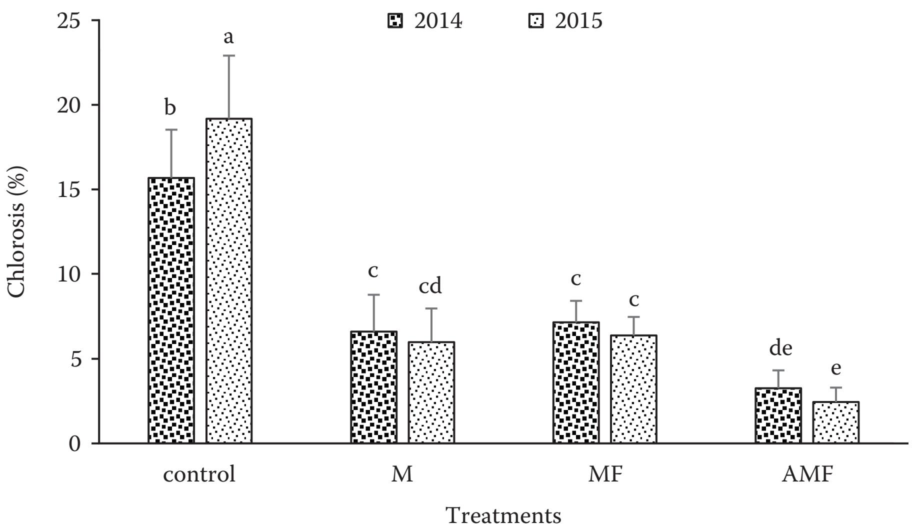

Figure 5. Influence of different treatments on chlorosis in plane tree

[a–e] Means followed by same letter do not differ significantly by LSD tests at $P \leq 0.05$; M – manure; MF – manure + fertiliser; AMF – arbuscular mycorrhizal fungi (mixture of *Rhizophagus irregularis* and *Funneliformis mosseae*)

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instances, the effects may be variable or negligible. According to Bennett and Bever's (2007) findings, the inoculation with three distinct species of AMF had varying effects on the resistance of *Plantago lanceolata* plants to feeding by *Junonia coenia* butterflies. The outcome was dependent on the specific AMF and plant species involved, with some instances resulting in positive effects, others in negative effects, and still others in neutral effects. According to Roger et al. (2013), various species of AMF evoke varying effects on plant growth and plant resistance to herbivory. According to Roger et al. (2013), larger and healthier plants are frequently targeted by sucking insects, irrespective of the arbuscular mycorrhizal fungi status of the plant. The results of this experiment indicate that insects exhibited a preference for consuming a greater quantity of leaves derived from plants that had been inoculated with AMF. Pests may be drawn to plants with larger leaves. The study conducted by Wurst and Forstreuter (2010) yielded results indicating the absence of any discernible influence of AMF colonisation on the preference of aphids (*Myzus persicae* Sulzer). However, it was observed that the plants inoculated with AMF exhibited greater biomass as compared to those that were not inoculated. The study observed that the application of AMF in *Phaseolus vulgaris* L. bean plants resulted in an increase in the population of *Tetranychus urticae* Koch, as compared to the non-inoculated plants, which is consistent with the findings of Hoffmann et al. (2011). The study conducted by Gange et al. (1999) demonstrated a rise in the performance of aphids, specifically *Myzus ascalonicus* and *M. persicae*, in *Plantago lanceolata* trees that were inoculated with AMF. The aphid population on the AMF-inoculated plants was observed to be seven times greater than that of the control plants.

According to Cornelissen et al. (2008), plants exhibiting accelerated growth rates tend to be more susceptible to a diverse range of pests, including Diptera, Homoptera, and Lepidoptera. The biological capacity of insect herbivores and their population can be influenced by the quality of the host plant. According to Vannette and Hunter (2009), herbivorous pests are primarily drawn toward plants that possess a greater concentration of nitrogen and phosphorus in their tissues. The level of nitrogen present in the plant is regarded as one of the key determinants of host plant quality. Research has indicated that insects with a sucking feeding mechanism exhibit a significant response to the presence of nitrogen in plants (Van Emden 1966). The alteration of nitrogen fertilisers, whether increased or decreased, has the potential to affect the quality of host plants for insect herbivores, thereby influencing their growth and fertility rates. This has been demonstrated in various studies, including those conducted by Larsson (1989), Nevo and Coll (2001), and Wang et al. (2006). Numerous studies have demonstrated that elevated levels of nitrogen are associated with elevated growth rates and population sizes of sap-sucking pests.

Several researchers (Wu et al. 2017; Aalipour et al. 2019, 2020, 2021) have reported an increase in the concentration of nitrogen (N) and phosphorus (P) in plants that were inoculated with AMF. It is noteworthy that AMF lack the direct ability to decompose organic matter. Nevertheless, it is worth noting that fungal hyphae exhibit a higher degree of efficiency in penetrating decomposing material compared to plant roots, as per Javaid's research (Javaid 2009). Consequently, the inoculation with AMF resulted in an increase in both the size and quality of the plant, potentially due to alterations in nutrient uptake mechanisms (Smith, Read 2008; Aalipour et al. 2021). Additionally, the changes in the populations of insect herbivores as a result of AMF have been linked to modifications in the quantity, quality, defence mechanisms, or tolerance to pests in host plants (Gange et al. 1999). The inoculation of tomato (*Lycopersicon esculentum* Mill.) plants with AMF resulted in a reduction in the feeding activity of beet armyworm (*Spodoptera exigua* Hübner) in comparison with those insects that fed on non-inoculated plants. According to Shrivastava et al. (2015), there is evidence to suggest that AMF plants exhibit a stronger resistance response to herbivore feeding compared to non-inoculated plants, which may partially be due to variations in terpenoid levels. According to Pineda et al. (2010), plants inoculated with AMF may exhibit an increase in the production of secondary metabolites that possess toxic properties to pests. These compounds are known to be synthesised through enzymatic hydrolysis. Chewing insects are known to employ enzymes that facilitate the release of cell contents upon contact with secondary metabolites, resulting in the production of hazardous combinations that are detrimental to their survival. However, sucking

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pests have developed a mechanism to counteract this challenge. According to Walling (2008), the sucking organs of these pests prevent the formation of a connection between hydrolyzate enzymes and secondary metabolites by penetrating the phloem. Consequently, the production of toxic metabolites is inhibited. According to Hartley and Gange (2009) and Gehring and Bennett (2009), there appears to be a reduced impact of the defence mechanism activated by AMF in the host plant on sucker pests.

Alterations in the primary metabolite composition, specifically the soluble carbohydrates, within plants inoculated with AMF have been observed to have an impact on insects that consume said plants (Gehring, Witham 1994). The symbiotic relationship between AMF and the host plant results in a modification of the carbon, nitrogen, and carbohydrate levels, as reported by Wu et al. (2015) and He et al. (2017). According to Gehring and Witham's (1994) findings, the inoculation with mycorrhizal fungi in plants can lead to an increase in soluble carbohydrate content, which may potentially enhance the growth of insects. According to Gange and West's research (Gange, West 1994), a decrease in leaf carbohydrates results in a decline in insect performance, whereas an elevation in nitrogen levels leads to an improvement in insect performance.

According to Gange et al. (1999), there is evidence to suggest that the colonisation of AMF may have a positive impact on the life history traits of phloem feeders, such as growth rate and reproductive success. The observed rise in feeding potential could be attributed to various factors such as increased leaf area, plant height, and biomass, as reported by Simon et al. (2017b). Our findings suggest that the enhanced nutritional status of the plant, facilitated by the fungi, is a probable contributing factor to the increased *Z. pulchra* population observed in AMF plants. However, the precise mechanisms through which arbuscular mycorrhizal fungi impact insect growth and population remain largely unexplored. Consequently, to comprehend the mechanism of AMF-insect interactions, it is necessary to conduct a comparative analysis of insect preference and performance on both AMF and non-AMF plants. To the best of our knowledge, there have been no similar findings regarding the impact of AMF inoculation on the population and the efficacy of *Z. pulchra* in plane trees.

CONCLUSION

The findings of this research indicate that the population of *Z. pulchra* and the resulting leaf damage can be increased by the addition of AMF. It is widely acknowledged that the performance of herbivorous insects is closely linked to the availability of food supplied by plants. In this regard, it has been observed that the presence of arbuscular mycorrhizal fungi with plane trees can enhance the nutrient and soluble sugar content, thereby improving the performance and population of *Z. pulchra*. Although nutritional strategies may account for certain triple responses observed among AMF, insects, and plants, further exploration is necessary to examine alternative mechanisms. Nevertheless, it is believed that the benefits of mycorrhizal fungi on plane trees are outweighed by the negative consequences of raised appeal to *Z. pulchra*.

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Forest cover change detection using Normalized Difference Vegetation Index in the Oued Bouhamdane watershed, Algeria – A case study

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Abstract: The Algeria forest, particularly in the northeastern region, has undergone profound changes in recent years. The Oued Bouhamdane watershed has a great forest potential, which is threatened by several factors of natural and human origin, resulting in a decrease in forest cover. It requires adequate forest monitoring to support the sustainable forest management of this watershed, which is possible thanks to satellite imagery. The objective of this research is to study the spatiotemporal dynamics of the vegetation cover of the Oued Bouhamdane watershed between 2013 and 2022 using remote sensing data. This study is based on the use of Landsat 8 and 9 images for two dates in 2013 and 2022, and the calculation of the Normalized Difference Vegetation Index (*NDVI*) to identify changes in vegetation cover between 2013 and 2022. The calculation of *NDVI* and the realization of the vegetation change map showed a regression of the forest cover between 2013 and 2022 with a rate of –5.53% of the total of the study area with a general negative change of 28.62% of the study area. This regression is essentially linked to natural and anthropogenic factors. This work can be a valuable tool for sustainable management of the forest of this watershed; moreover, the method is also adaptable to other watersheds of the northeastern region of Algeria.

Keywords: remote sensing; GIS; indices; degradation; Landsat

The global forest cover is a major indicator of the health of our planet. A natural, non-degradable forest provides many services, including nutrient recycling, climate regulation, soil stabilization, waste recycling and the creation of natural habitats, not to mention a wide range of recreational activities and outdoors (Larsen 2003). The global forest is shrinking. From year to year, it loses area. Even today, it still covers some 40 million km^2 (Mayer 2022). The forest cover in Algeria is spread over an area of 1.3 million ha of real natural forests (Barbache 2021). These forests have experienced an almost exponential regression in recent years, and are today in an appalling state (El Zerey 2014). Poorly managed Algerian forest biodiversity is deteriorating due to the loss of natural resources (Haichour et al. 2022). The forest cover of the Oued Bouhamdane watershed presents a concrete illustrative example of intense degradation in an area where climatic factors and human activities are combined, contrary to the idea of sustainable management and development of the forest area. In this watershed, which is characterised by an important forest heritage and hydrographic network, the forest cov-

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er is today facing illegal cutting, overgrazing, clearing, agricultural extension and devastating fires. A better understanding of the evolution of forest cover is a major concern for countries whose forest cover is undergoing severe degradation. Indeed, the dynamics of this forest cover has direct implications on the availability of natural resources (Bouidjra et al. 2011). The use of remote sensing to study forest cover is a major asset with high spatial resolution satellite data (Hansen et al. 2008). In Algeria and more specifically in the Batna Province, the study and diachronic analysis of changes in the forest cover of Belezma were carried out by Barbache et al. (2019) using vegetation indices. However, vegetation indices are very useful for assessing forest cover performance (Morton et al. 2006). One of the most widely used indices for monitoring forest cover is the Normalized Difference Vegetation Index (*NDVI*) (Nath et al. 2013). According to Ghebrezgabher et al. (2016), *NDVI* is the most widely used factor in vegetation studies. To calculate *NDVI*, we use the reflectance of the red (R) and near infrared (NIR) bands measured in the visible band by sensors on board drones or satellites (Alexandre 2020). In theory, *NDVI* values for vegetation tend towards 1 while those in no vegetation areas tend towards –1. Thus, the more the proportion of vegetation decreases, the more the red reflectance values tend to decrease linearly, so that the relationship between plant cover in percentage and *NDVI* values is linear (Beck et al. 2006). The objective of this study is the detection of forest cover changes, based on *NDVI* using Landsat program images acquired in different years. This approach is part of the protection and preservation of the forest cover of this watershed, and this of course to protect it from the phenomenon of soil erosion.

MATERIAL AND METHODS

Study area. The Oued Bouhamdane watershed is one of the major tributaries of the Seybouse with an area of 1 108 km^2 (Khallef et al. 2020). It is located in the northeast of Algeria, it is part of the Seybouse watershed and results from the junction of three major rivers: Oued Sabath, Oued Zenati and Oued Sakkoum (Bouguerra 2018). Under the Seybouse watershed, its limits are part of the territory of three wilayas; these are the southwestern part of the Guelma wilaya, the eastern part of the Constantine wilaya, and the southern part of the Skikda wilaya. It is limited to the north by the coast Constantinois watershed, to the south and southeast by the Oued Cherf watershed, to the east by the middle Seybouse watershed and to the west by the Kebir Rhumel watershed (Figure 1).

It has an elongated shape; it is drained by Oued Bouhamdane and its tributaries. The relief of this watershed is characterised by a significant altitudinal variance, ranging from 997 m to 1 237 m at Djbel Oum Settas. The lithology encompasses a multitude of lithological formations composed mainly of Numidian sandstones, clays, marls, limestones, marl-limestones, shales, conglomerates and superficial formations. These facies, ranging from the Quaternary to the Triassic, present variations in facies resistance ranging from the hardest rocks represented by limestone and sandstone rocks to the softer clayey rocks (Bouguerra 2018). The climate of the study area is of the Mediterranean type characterised by a cold, rainy winter and a dry and hot summer. The average annual rainfall varies from 644 mm to 932 mm. The rainiest months are January, February and March, totalling 237.63 mm, with a maximum rainfall that reaches the value of 81.92 mm recorded during the month of February for the period 2009–2022. The average temperature is 18 °C, the average minimum temperature is 4.68 °C in February, while the average maximum is 36.81 °C for the month of July. The vegetation cover of the study area consists mainly of a rugged mountain forest. A forest system is balanced when consisting of three strata, namely tree, shrub and herbaceous stratum of various age groups. The inspection of the field shows that there is a dominance of the tree and shrub training formations found in the form of forest and maquis, which are generally represented by *Quercus coccifera, Quercus suber, Erica arborea, Calycotome spinosa, Phillyrea angustifolia, Olea oleaster, Pistacia lentiscus, Cistus monspeliensis, Ceratonia siliqua*, and *Crataegus monogyna.* However, the herbaceous stratum is represented by lawns and brush, followed by shrub vegetation in the form of maquis and the understorey of the forest. On the along with Oued Bouhamdane, there are ripisylves dominated by *Nerium oleander*, *Tamarix gallica*, and *Mentha aquatica*.

Methodology. The methodology followed in this study is based on the use of *NDVI* to detect changes in forest cover at the scale of the Oued Bouhamdane watershed for a period of 9 years (2013–2022). This

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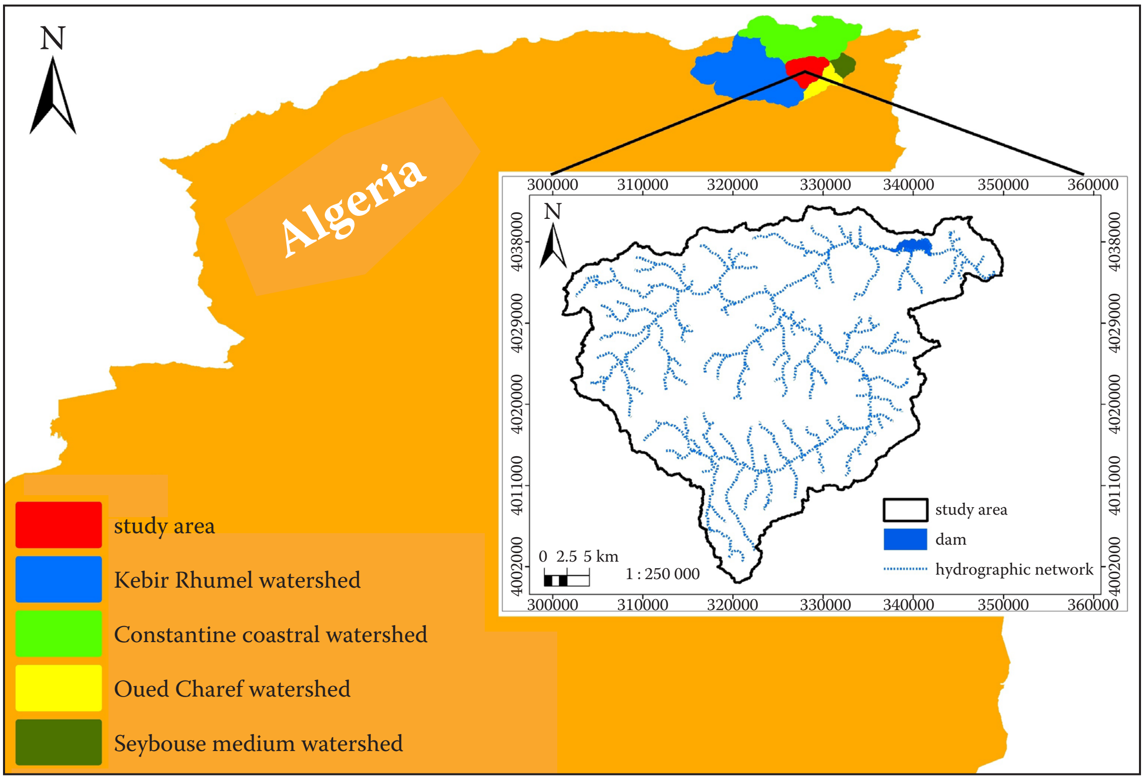

Figure 1. Location of the study area

methodological approach comprises three phases, summarised and developed below (Figure 2).

Data collection. This study is based on two medium-resolution (30 m) satellite images from the Landsat program during the period of 2013 and 2022, downloaded from the US Geological National Center (USGC). Landsat 8 OLI was acquired on July 25, 2013 and Landsat 9 OLI-2

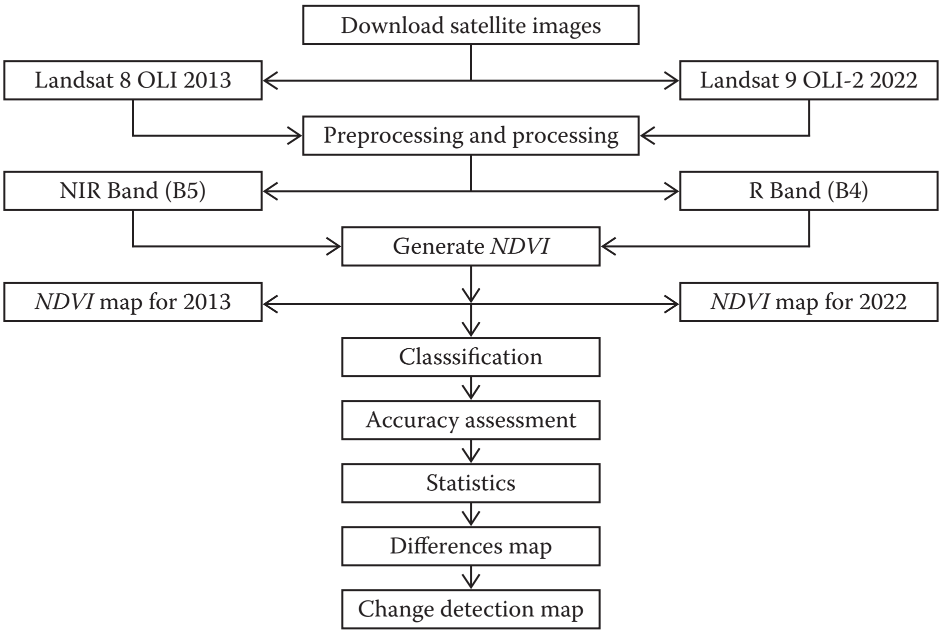

Figure 2. Flowchart for change detection in forest cover between 2013 and 2022

NIR – near infrared; R – red; *NDVI* – Normalized Difference Vegetation Index

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on July 26, 2022 (Table 1). The basic satellite images of this work were all acquired during the dry season, the period of maximum differentiation of forest cover compared to other elements of land use. The preprocessing and image processing were carried out using ENVI (Version 5.1, 2015) and ArcGis (Version 10.6.1, 2015) software. The spatial resolution is 30 m and the projection system applied to all our data is Transverse Mercator zone 32 north.

Image processing. The *NDVI* values vary from –1 to 1. The low values of *NDVI* correspond to the sterile areas of rock, sand, snow, clouds. Moderate values represent shrubs and meadows, while high values indicate a dense vegetation cover. The bare soil is represented with *NDVI* values which are closest to 0 and the water bodies are represented with negative *NDVI* values (Xie et al. 2010). The *NDVI* is a vegetation index used to estimate the quantity, quality and development of vegetation, from the measurement of the radiation intensity of certain bands of the electromagnetic spectrum that the vegetation emits or reflects (Rouse et al. 1973). The *NDVI* is calculated by the following formula:

$$NDVI = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}} \quad (1)$$

where:

NIR – near infrared (Band 5 for Landsat 8 and Landsat 9);

R – red (Band 4 for Landsat 8 and Landsat 9).

For the two chosen observation dates, each calculated Normalized Difference Vegetation Index is classified into ranges. The *NDVI* values for areas of barren rock, sand or snow generally have very low values corresponding to classes (no vegetation). The low values that represent shrubs and grasslands are the sparsely vegetated classes while senescent crops can result in moderate values – these are the moderately vegetated classes. High to very high *NDVI* values correspond to high and dense vegetation, respectively (USGS 2018).

Class determination. The overlay of thematic maps, in particular, the vegetation map drawn up by the BNEF (National Bureau of Forest Studies) on the one hand, and the information acquired during field surveys on the other hand, made it possible to determine five classes which are: (*i*) no vegetation – this class looks like what is bare soil, ploughland, rocks, urban, barren land and body of water where the vegetation is totally nil; (*ii*) sparse vegetation represents shrubs and meadows; (*iii*) moderate vegetation stands for rangelands and senescent crops; (*iv*) high forest is Mediterranean-type maquis composed mainly of Cistus, heather, lentisk, thorny Calycotome, wild olive, *Phillyrea latifolia* and other species; (*v*) dense forest – this class represents the state forests of Taya and Beni Medjaled. The forest cover of this class is characterised mainly by cork oak, zeen oak and reforestation of eucalyptus and other species.

***NDVI* classification.** According to the value of *NDVI*, the image can be classified by means of the method adopted for the study, which is the supervised classification, with the 'Maximum likelihood' algorithm used as an approach leading to the identification of homogeneous samples in images representative of both types of surfaces (vegetation and no vegetation) (Congalton 1991). These samples then form a set of test data (Soudani 2006). The choice of test data is based not only on the surface types identified in the images but also on the knowledge of the terrain. The intensive visual analysis of our images, the use of Google Earth support, the information acquired during the field surveys and the visual interpretation of the satellite image provided a general idea of the components of the study area (Khallef et al. 2021).

Accuracy assessment of classification. The classification of an image is not complete until its accuracy is assessed. To determine the accuracy of the classification, a sample of test pixels must be selected in the classified images and their class identity to compare it with the reference data (ground reality). Overall accuracy is a standard criterion used to assess the accuracy of classifications. Overall accuracy is defined as the total number of correctly classified pixels divided by the total number of reference pixels (Rogan et al. 2002). To assess the ac-

Table 1. Dates and characteristics of Landsat images used

Sensor	Acquisition date	Path/Row	Resolution (m)	Bands used
Landsat 8 OLI	July 25, 2013	193/035	30	B5, B4
Landsat 9 OLI-2	July 26, 2022	193/035		

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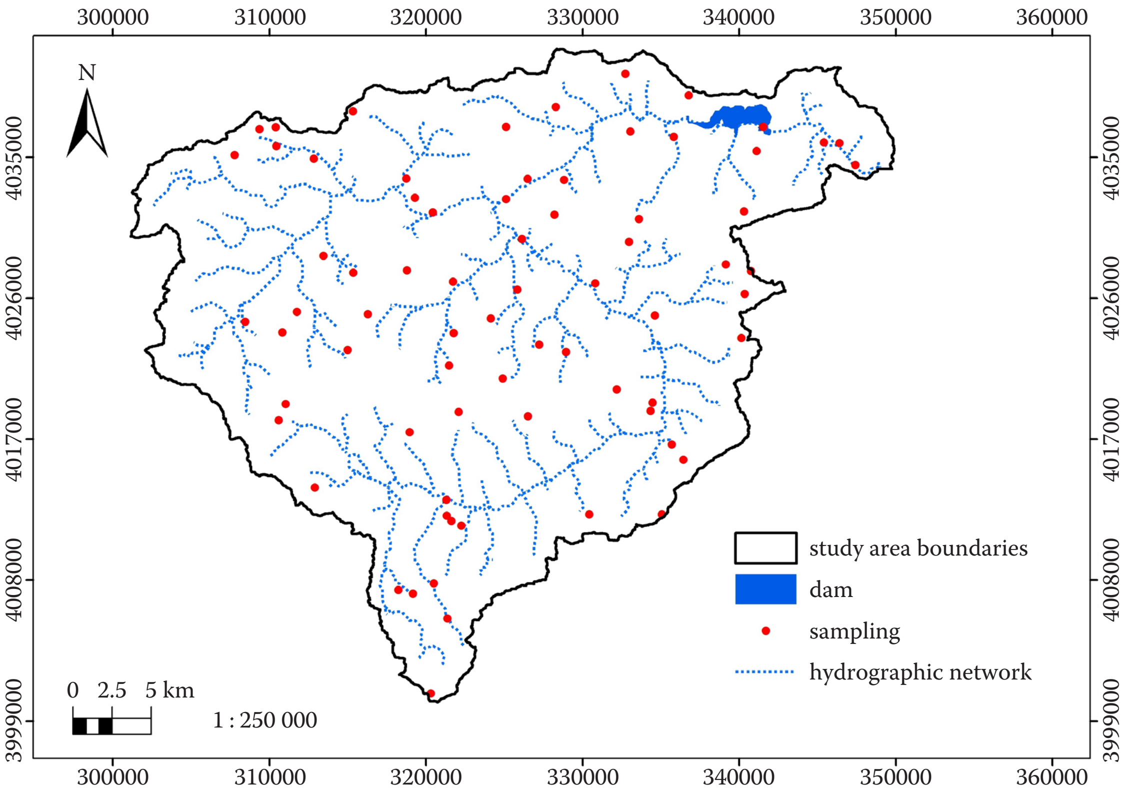

Figure 3. Reference points

curacy of the *NDVI* supervised classification result of 2013 and 2022, a comparison is made with high-resolution images from Google Earth for the two observation dates (2013, 2022). 72 reference points are randomly selected using the Create Accuracy Assessment toolbox (Version 7, 2011) for the two classified *NDVI*. Then the 72 points created for each classified *NDVI* are displayed in Google Earth to compare the result obtained by supervised classification with reality (Figure 3). The level of precision is calculated on the basis of reference data using Google Earth images for the two reference dates followed by a verification of the ground**.**

Change detection. Change detection evaluates and identifies any difference change between two images in the same study area on different dates (Hegazy et al. 2015). In this study, image differentiation is used by subtracting the recent image from the old one to find out the extent of the change. Change detection was calculated using post-classification change techniques or map-to-map change detection; it is a process of overlaying coincident thematic maps of different time periods to identify changes between them. The distinct advantage of this technique is that the basic classification and change transitions are explicitly known. Direct comparison of satellite-derived land cover maps is one of the most established and widely used change detection methods applicable to Landsat-class imagery (Tewkesbury et al. 2015). This change detection is calculated as follows:

$$\Delta NDVI_{2013/2022} = \quad (2)$$
$$= NDVI(\text{classified})_{2022} - NDVI(\text{classified})_{2013}$$

RESULTS

The *NDVI* has been widely used to study the relationship between spectral variation and changes in the vegetation growth rate. It is also useful for determining green production as well as detecting vegetation changes (Perminder 2021). In the case of the vegetation cover of the Oued Bouhamdane watershed, the result of the calculation of the *NDVI* of the two dates chosen is represented in Figures 4 and 5.

The range of *NDVI* values in the 2013 image varies from –0.08629 to 0.5107 and in the 2022 image from –0.1220 to 0.4941. A high *NDVI* value indicates high vegetation density while a lower *NDVI* value indicates low vegetation density. According to Figures 4 and 5, the *NDVI* values for the year 2013 are

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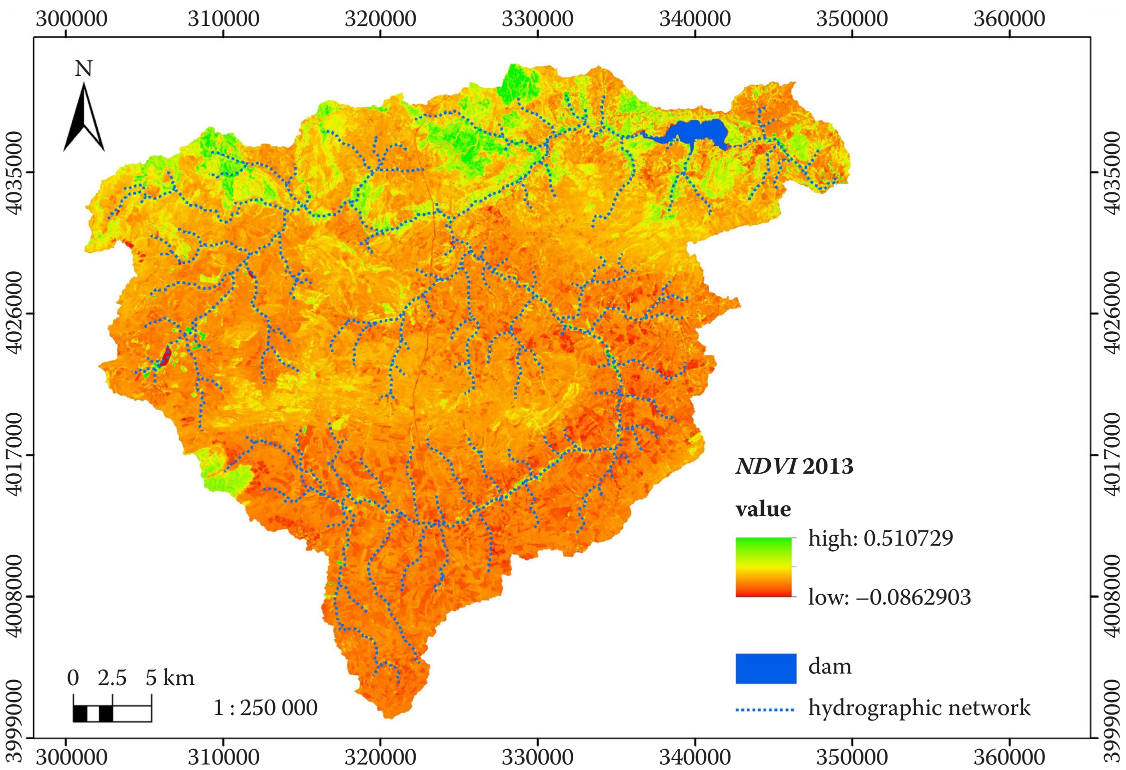

Figure 4. *NDVI* map of the study area in 2013

NDVI – Normalized Difference Vegetation Index

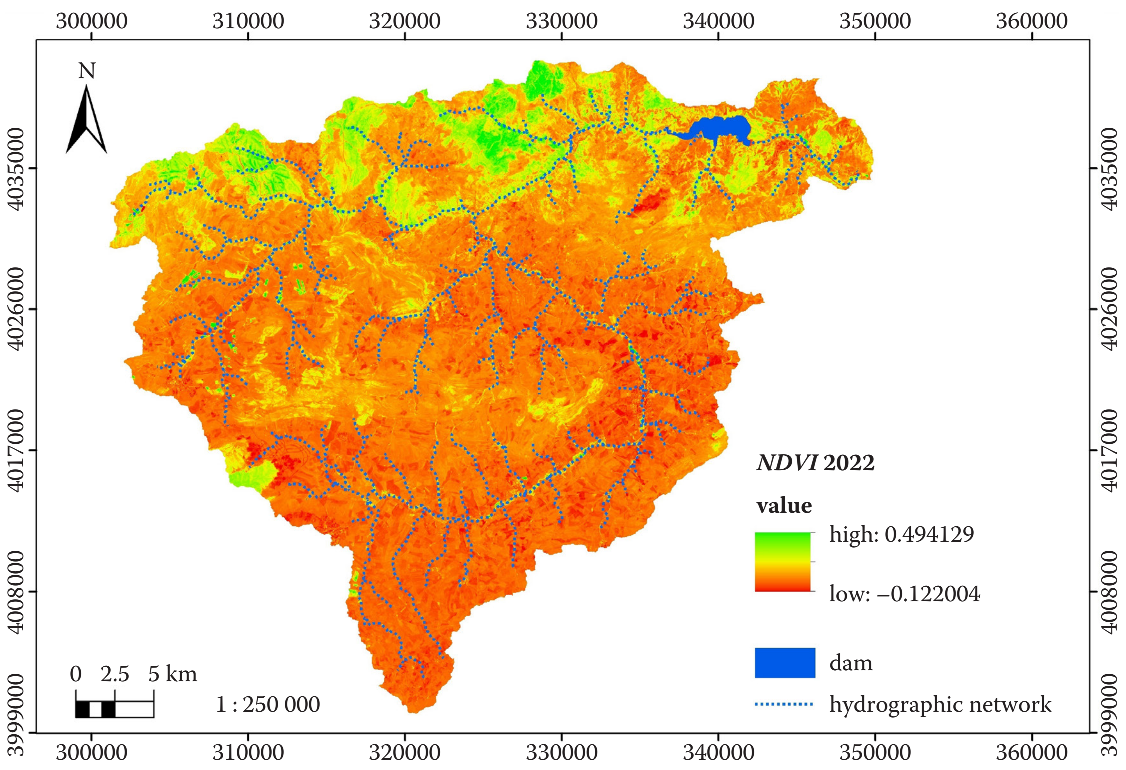

Figure 5. *NDVI* map of the study area in 2022

NDVI – Normalized Difference Vegetation Index

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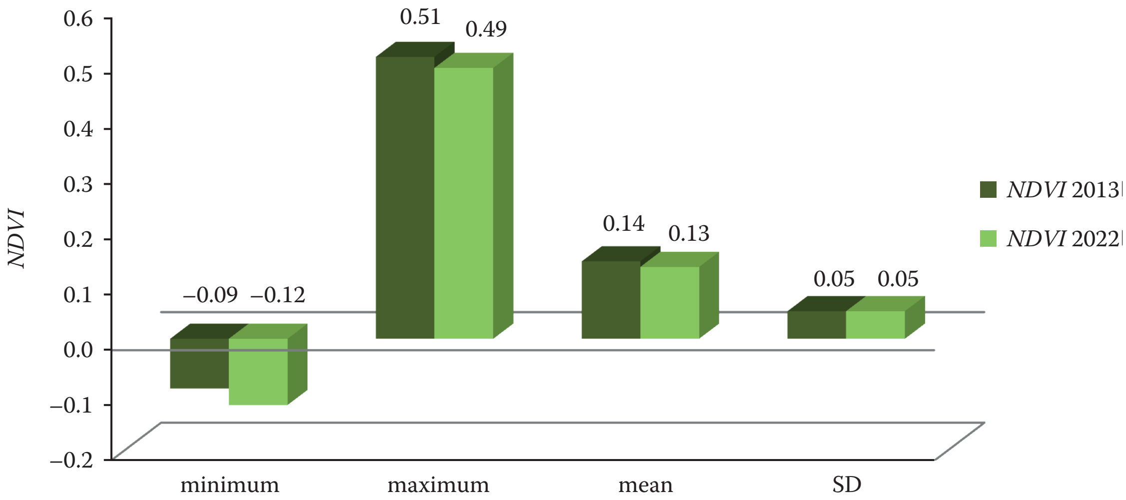

Figure 6. *NDVI* values for the years 2013 and 2022

NDVI – Normalized Difference Vegetation Index

higher than those of the year 2022, and the maximum value of the *NDVI* decreases by 0.02, which provides information on the decrease in vegetation cover during this observation period. Figure 6 shows that the *NDVI* values of 2013 are significantly higher than the *NDVI* values of 2022. The average *NDVI* value for 2013 is estimated at 0.14 while the average *NDVI* value for 2022 is 0.13.

The result of the *NDVI* supervised classification of the Landsat images from 2013 and 2022 made it possible to observe and quantify the state of the evolution of the forest cover in the Oued Bouhamdane watershed, and to highlight its different changes occurring during 9 years, thus obtaining good quality maps (Figure 7 and 8). On the one hand, this is due to the date on which the satellite

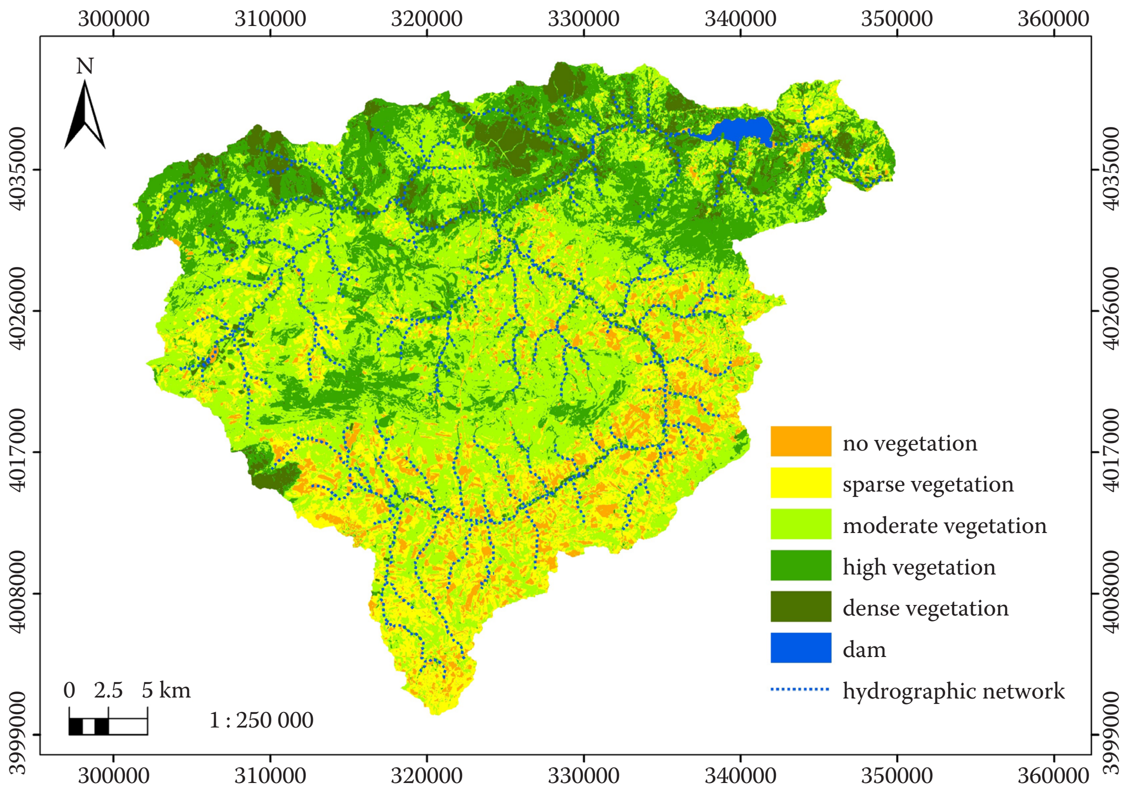

Figure 7. Map of classification of vegetation classes for the year 2013

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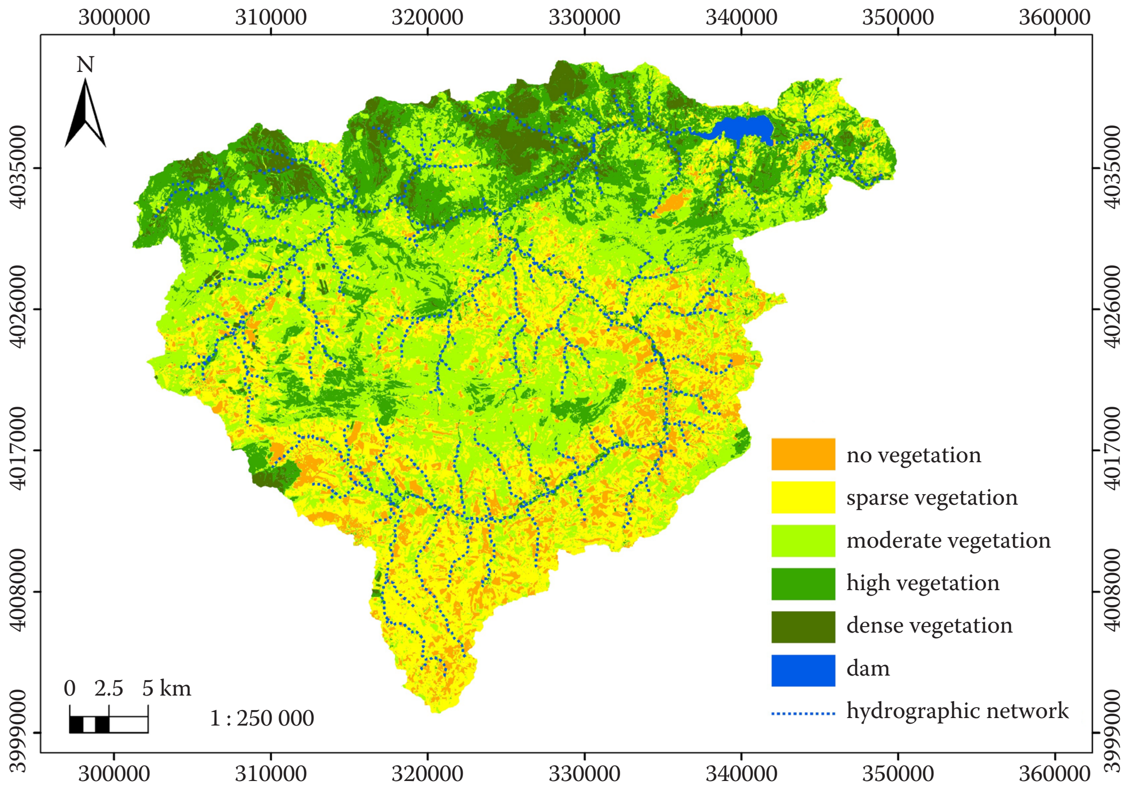

Figure 8. Map of classification of vegetation classes for the year 2022

images were taken in the dry season and on the other hand to field verification.

The level of accuracy of the results obtained for the classified *NDVI* retained for the year 2013 is 87.5%, the Kappa coefficient is 83.76%, whereas the level of accuracy calculated for the classified *NDVI* retained for the year 2022 is around 83.33% with the Kappa coefficient estimated at 78.48% (Tables 2 and 3).

Dynamics of forest cover between 2013 and 2022. The resulting *NDVI* map from the 2013 classification reveals that forest cover (high vegetation and dense vegetation) occupied 30.85% or 34 178.40 ha of the total study area. For the classified *NDVI* map used for the year 2022, the forest cover accounts for an area of 28 054.89 ha, or for 25.31% of the total study area (Table 4).

Table 4 shows that the classes of high vegetation decreased from 27 833.49 ha in 2013 to 22 285.89 ha in 2022; the same applies to the classes of dense vegetation which were estimated at 6 344.91 ha in 2013 but reached only 5 769 ha in 2022. These two classes (high vegetation, dense vegetation) really represent the forest cover in the Oued Bouhamdane watershed, unlike the classes which have no cover or have low veg-

Table 2. Statistics of assessment accuracy of the *NDVI* (2013)

Class	No vegetation	Sparse vegetation	Moderate vegetation	High vegetation	Dense vegetation	Total user	User accuracy	Producer accuracy
No vegetation	9	1	0	0	0	10	90.00	100.00
Sparse vegetation	0	11	0	0	0	11	100.00	61.11
Moderate vegetation	0	3	23	0	0	26	88.46	92.00
High vegetation	0	2	2	11	–	15	73.33	100.00
Dense vegetation	–	1	–	–	9	10	90.00	100.00
Total	9	18	25	11	9	72	441.79	453.11

NDVI – Normalized Difference Vegetation Index

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Table 3. Statistics of assessment accuracy of the *NDVI* (2022)

Class	No vegetation	Sparse vegetation	Moderate vegetation	High vegetation	Dense vegetation	Total user	User accuracy	Producer accuracy
No Vegetation	8	2	0	0	0	10	80.00	61.54
Sparse vegetation	2	16	0	0	0	17	94.12	76.19
Moderate vegetation	2	3	18	0	0	23	78.26	85.71
High vegetation	0	0	3	9	0	12	75.00	100.00
Dense vegetation	1	0	0	0	9	10	90.00	100.00
Total	13	21	21	9	9	72	417.38	423.44

NDVI – Normalized Difference Vegetation Index

Table 4. *NDVI* classification statistics for the year 2013 and 2022

Class	*NDVI* 2013		*NDVI* 2022	
	area (ha)	area (%)	area (ha)	area (%)
No vegetation	8 471.88	7.64	10 363.59	9.36
Sparse vegetation	20 583.81	18.58	30 687.93	27.70
Moderate vegetation	47 569.68	42.93	41 697.36	37.63
High vegetation	27 833.49	25.12	22 285.89	20.11
Dense vegetation	6 344.91	5.73	5 769.00	5.20
Total	110 803.77	100.00	110 803.77	100.00

NDVI – Normalized Difference Vegetation Index

etation (no Vegetation, sparse vegetation) which represent an area of 2 905 569 ha in 2013 against 41 051.52 ha in 2022. However, the moderate vegetation classes are not considered forest cover; the area of these classes varies from 47 569.68 ha in 2013 to 41 697.36 ha in 2022.

Change detection. The calculation of Δ*NDVI* by applying Equation (2) reveals changes in forest cover within the Oued Bouhamdane watershed during the period considered (Table 5).

Table 5 shows different evolutions (progression or regression) of the vegetation cover during 9 years of observation. No vegetation classes increased from 8 471.88 ha in 2013 to 10 363.59 ha in 2022, showing a growth of 1.71% – this is mainly due to the increase in urban and agricultural areas. The sparse vegetation classes vary from 20 583.81 ha in 2013 to 30 687.93 ha in 2022, thus showing an upward trend of 9.12%, indicating deforestation in these areas. However, the classes of moderate vegetation estimated at 47 569.68 ha in 2013 reached 41 697.36 ha in 2022, which represents a regression of –5.30% compared to the year 2013. The classes that actually represent the forest cover (high vegetation and dense vegetation) go from 34 178.4 ha in 2013 to 28 054.89 ha in 2022, which generates

Table 5. Area changes of vegetation classes during the observation period (2013–2022)

Class	Change detection between 2013 and 2022		Average rate (ha·year^{-1})
	area (ha)	area (%)	
No vegetation	+1 891.71	+1.71	+210.19
Sparse vegetation	+10 104.12	+9.12	+1 122.68
Moderate vegetation	–5 872.32	–5.30	–652.48
High vegetation	–5 547.60	–5.01	–616.40
Dense vegetation	–575.91	–0.52	–63.99
Total	0.00	0.00	0.00

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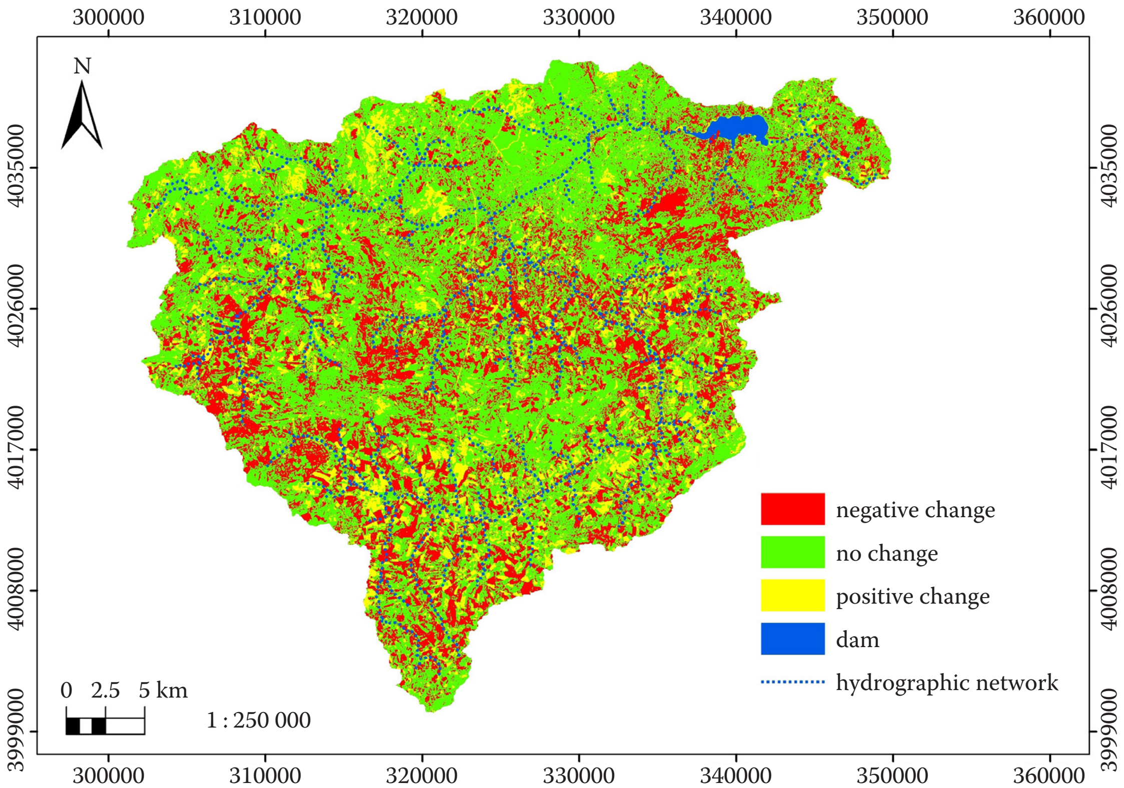

Figure 9. Map of vegetation changes between 2013 and 2022

a negative change of –5.53%. According to Table 5, the Oued Bouhamdane watershed loses 680.39 ha of its forest cover annually for the 2013–2022 observation periods, which explains the increase in the area of no vegetation and sparse vegetation classes. This regression is mainly due to natural and anthropogenic factors (repeated fires, drought, clearing, illegal cutting, overgrazing). The established change map spatially and quantitatively illustrates significant changes in the vegetation cover that occurred in the Oued Bouhamdane watershed over a 9-year period (2013–2022). These changes in vegetation are represented by three classes which are: (*i*) the class of positive changes for the zones where the vegetation has progressed, (*ii*) the class of negative changes for the zones where the vegetation has undergone a regression, and (*iii*) the class of zero changes for the zones of stability (Figure 9).

Table 6. Vegetation changes between 2013 and 2022

Type of change	Area (ha)	Area (%)
Positive	13 440.51	12.13
Negative	31 709.07	28.62
No change	65 654.19	59.25
Total	110 803.77	100.00

Figure 9 shows that the regression zones (negative changes) are mainly located in the central, northeastern, southern and southwestern part, with the rate of 28.62% or 31 709.07 ha of the total area of the perimeter of the study. However, the areas of positive changes have increased to 13 440.51 ha, i.e. a rate of 12.13% of the total study area. This progression is concentrated mainly in the southern, central and northern part, while the stability zones cover almost the entire territory of the watershed, covering 59.25% with an area of 65 654.19 ha (Table 6).

DISCUSSION

In general, the carried out diachronic study makes it possible to judge that the forest cover of the Oued Bouhamdane watershed is subject to an upheaval which leads to its regression. This regression is reflected in the decrease in the maximum *NDVI* value of 0.51 in 2013 to 0.49 in 2022. The rate of changes that was found by the verification of the ground and that reached 28.62% of the total surface of the watershed confirms that the situation of the vegetation cover of this area is alarming. We point out that the rate of vegetation regeneration is always dependent on the sanitary state of the vegetation

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cover, the regression factor and the climatic conditions of the region. The baring of the soil by the factors of clearing, fires, overgrazing and urbanization promotes the phenomenon of erosion. The repetitive passage of fires exposes the soil to water erosion and makes the regeneration of the vegetation cover more and more problematic. The missions organised during the field inspection show that human impacts are present and visible. These human attacks undoubtedly remain the determining factor in the regressive evolution of the vegetation cover in this watershed. The populations close to the forest exercise practices on the forest which still persist such as clearing, overgrazing, browsing, illegal cutting, especially on the cork oak and the zeen oak. All these actions were at the origin of the regression of the forest cover of the state forest of Beni Medjaled and Taya. Between 2013 and 2022, the burned forest area (cork oak, zeen oak, reforestation and maquis) on the scale of this watershed amounted to 1 200 ha, i.e. an average of 133.33 ha·year^{-1}. The methodological approach based on the use of *NDVI* to detect changes between 2013 and 2022 on the scale of the Oued Bouhamdane watershed shows an effective close to reality on the ground, if we compare the result obtained in this research with that obtained by other researchers in Algeria, such as Barbache et al. (2019) and others.

CONCLUSION

The monitoring of vegetation change in the Oued Bouhamdane watershed was conducted by the *NDVI* differentiation method applied using Landsat images taken in 2013 and 2022. This monitoring made it possible to highlight the major changes in the study area. The calculation of *NDVI* for the two chosen reference dates shows that the maximum values of the *NDVI* for the year 2013 are higher than those of the *NDVI* for 2022. The supervised classification of the *NDVI* from the years 2013 and 2022 made it possible to quantify the vegetation cover of the Oued Bouhamdane watershed. This quantification shows that the classes (High vegetation, Dense vegetation) which really represent the forest cover of this zone have undergone a regression which reaches –5.53% of the total area of the watershed. This regression is linked to multiple factors of aggression, mainly anthropogenic (overgrazing, deforestation, fires), which is currently destabilizing the ecological balance of this forest ecosystem. To protect this forest wealth, and in this region in particular, it is urgent to set up a management plan, and a monitoring and surveillance program in order to ensure better protection of this forest wealth in line with the current situation.

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Analysis of the propensity of Italian and German forest owners towards forest certification for ecosystem services

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Abstract: This study analyses the perception of the relationship between forest certification and the production of ecosystem services by Programme for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC) sustainable forest management (SFM) certification holders. In addition, the psychological constructs that govern the use of certification for ecosystem services are investigated. Specifically, online questionnaire surveys were submitted to a sample of Italian and German forest owners and managers to study reasons for and against and global motives to adopt certification for ecosystem services through the application of Behavioural Reasoning Theory (BRT). Results show that respondents believe that certification can better support ecosystem services related to 'regulation and maintenance' and the conservation of biodiversity. On the other hand, the application of BRT has only been partially useful in explaining the psychological factors towards the adoption of ecosystem services certifications. In any case, attitudes and reasons for certainly had a significant influence on the intention to adopt certifications. Apart from the scientific implications, these results have practical applications for policymakers who can focus on the dissemination of the certification of ecosystem services by trying to support through eco-policies, the attitudes and reasons for expressed by forest owners.

Keywords: behavioural reasoning theory; forest ecosystem services' certification; Forest Stewardship Council (FSC); Programme for the Endorsement of Forest Certification (PEFC); sustainable forest management

The European Union's forest territory accounts for about 5% of the world's, and in contrast to the rest of the world is slowly increasing (EUROSTAT 2020), providing not only timber production but also a wide range of non-wood forest products, as well as ecosystem services. According to the CICES classification (Common International Classification of Ecosystem Services), three macro-categories of ecosystem services can be distinguished: supply services, such as timber, spontaneous non-timber forest products, or water; regulation and maintenance services, such as soil erosion control, water purification, or carbon dioxide absorption; cultural services, related to the support of tourism, recreation, sports activities, cultural activities, or the preservation of landscape values. The last decade has seen a steady growth of alternative approaches by the European forestry sector towards a 'forest circular bioeconomy', mainly represented by an improvement in the environmental and cultural values of the forest, as well as the efficiency of forestry workers and the spread of forest certification (Paletto et al. 2017). As Bengston (1994) states, there has been a shift from strictly productive silviculture towards multifunctional silviculture, precisely at a time when demands for non-timber forest resources were beginning to grow. Considering this cultural change, ecosystem services can

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be seen as an innovation to improve the management of renewable biological resources to create new economic opportunities for the forest sector. These include PES (payment for ecosystem services), which can be seen as an effective way to finance the costs of forest conservation by offsetting the opportunity costs of forest development (Meijaard et al. 2011). PES also include certifications for ecosystem services, according to Programme for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC) standards. Indeed, certification often has an impact on the local economy, not only for the 'wood' supply chain but rather for the attention given to non-wood services and products. In particular, the ecosystem services generated by forests can help maintain rural and mountain economies through the creation of an ecosystem services market composed of those who use these services and those who ensure their maintenance and continuity. In this perspective, therefore, certification represents a tool that forest owners and managers can use to demonstrate the positive impacts of sustainable forest management (Paluš et al. 2021) also by valuing the ecosystem services that forests provide to the community. Hence the development of certifications for ecosystem services as tools that can enable forest owners and managers to expand the concept of forest management by opening new management directions, monitoring and verification of the impacts of management activities and new business opportunities (FSC Italia 2021b). These standards specifically certify carbon sequestration and storage, biodiversity conservation, water regulation services, soil conservation and recreational services. In Europe, 17 entities are certified for ecosystem services according to the FSC standard, present in France, Germany, Italy, the Netherlands, Portugal and Spain (FSC 2022), and four according to the PEFC standard, present in Italy (PEFC Italia 2022).

Given this background, this study aims to analyse the perception of the relationship between forest certification and the production of ecosystem services by PEFC and FSC certification holders. From this perspective, the adoption of certification results from the combination of personal interests and company resources that influence forest owners and managers in the choice of certification (decision-making process). In fact, the study also aims to investigate the psychological constructs that govern the use of certification for ecosystem services through the analysis of empirical data from a survey conducted among Italian and German FSC and PEFC sustainable forest management (SFM)-certified owners and managers. The behavioural reasoning theory was applied to study the influence of reasons for and against, and global motivations to adopt certification for ecosystem services. The peculiar selection of the study areas is due to the desire to investigate the phenomenon of the spread of forest certification and, more specifically, certification for ecosystem services, with little insight into these two geographical areas. In the Italian case, in fact, although standards to certify ecosystem services were developed by both FSC in 2014 and PEFC in 2021, no study to date has analysed the intentions of forest owners to adhere to the ecosystem services certification standard. A similar situation exists in Germany, where certification standards for ecosystem services are still being disseminated.

Theoretical model and research hypothesis. The work adopts a conceptual framework based on the behaviour reasoning theory (BRT) to assess not only the intention towards the adoption of certification for ecosystem services, but primarily to examine 'resistance factors' and 'adoption factors' with respect to attitude and intention (An et al. 2021). The BRT finds its basis in two theories, the theory of reasoned action (TRA) and the theory of planned behaviour (TPB). They find application in explaining and predicting behaviour in a multitude of domains (Ajzen 2020). Specifically, in forestry, TPB is often used in relation to the forest owners' choice to adopt particular silvicultural methods (Karppinen 2005), or, more generally, to an interest in adopting sustainable management practices (Bieling 2004; Fielding et al. 2005; Rasamoelina et al. 2010; Ofoegbu, Speranza 2017) suitable for example for the production of carbon offsets (Thompson, Hansen 2012) or integrated with techniques for the conservation of biodiversity (Primmer, Karppinen 2010). The theoretical idea characterising TRA is that individuals act on the basis of perceived outcomes of their behaviour (Fishbein, Ajzen 1975; Ajzen, Fishbein 1980). When such outcomes are favourable, individuals form the intention to repeat that same behaviour. In turn, behavioural intention is determined by attitudes towards a specific behaviour (attitudes) and subjective norms (subjective norms). Attitude represents 'a learned disposition to respond favour-

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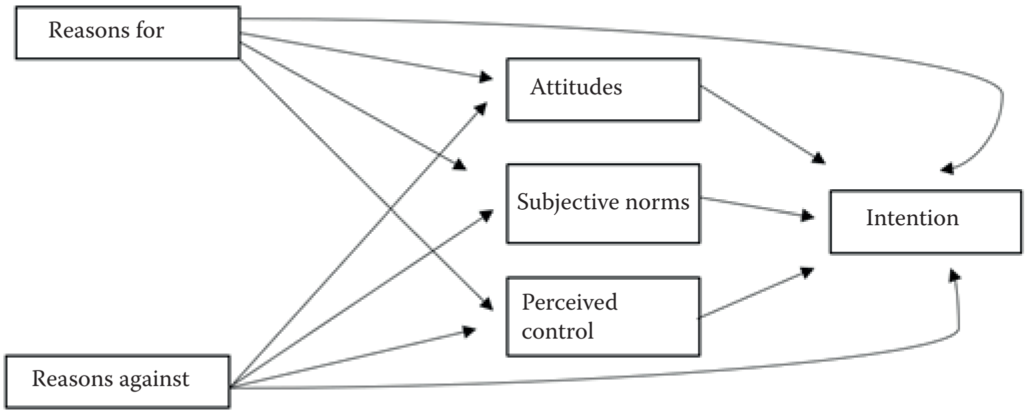

Figure 1. Applied research model

ably or unfavourably to a given object' (Fishbein, Ajzen 1975). Subjective norms refer to the individual consideration whether other individuals or referent groups (significant others, family, friends, neighbours, the community at large) perceive and evaluate their own behaviour favourably or unfavourably (Razali et al. 2020). If attitudes and subjective norms are favourable, intentions will prompt the subject to enact the behaviour. The TRA has certain limitations, as it can only explain voluntary behaviour, which requires skills, resources and opportunities. If the latter are not easily accessible, TRA does not find due application (Sok et al. 2020). For this reason, the theory of reasoned action was extended to include the perception of behavioural control (Ajzen 1991). Perceived behavioural control reflects the degree of perceived control a person has over their ability to perform a behaviour (Lalani et al. 2016). In this sense, intentions result in the execution of a behaviour only when external constraints, such as time and opportunities, and internal constraints, such as knowledge and skills, have been perceived as being under the control of the individual (Ajzen 1991). According to Westaby (2005), who proposed the BRT, specific motives serve as an important link between global motives (subjective norms, perceived behavioural control and attitudes), intention and behaviour. In fact, the author categorised the reasons into two groups: 'reasons for' and 'reasons against' the implementation of a given behaviour. These reasons were conceptualised by Westaby (2005) as 'pros and cons', 'costs and benefits', and 'facilitators and constraints' towards a behaviour. This theory is usually applied extensively in contexts concerning the adoption of innovations in the environmental field (Claudy et al. 2013, 2015) and often focuses on a holistic understanding of consumer behaviour (Dhir et al. 2021; Kumar et al. 2021). In this sense, in the context of forest certification, this theory is not yet applied.

Based on the theoretical frame of reference (Westaby et al. 2010), some specific research hypotheses were formulated as follows (Figure 1).

H_1: Subjective norms directly influence the intention of forest owners/managers to adopt certification for ecosystem services.

H_2: Personal attitudes directly influence intentions.

H_3: Perceived behavioural control positively influences the intentions towards ecosystem services (ES) certification.

H_4: Reasons for directly and positively influence intentions.

H_5: Reasons against directly and negatively influence intentions.

H_6: Reasons for positively influence attitudes, subjective norms and perceived behavioural control.

H_7: Reasons against negatively influence attitudes, subjective norms and perceived behavioural control.

MATERIAL AND METHODS

The survey population consists of forest owners, forest property managers or entities that have adopted PEFC and FSC certifications for SFM in both Italy and Germany, considering that certification for ecosystem services is directly linked to SFM certification. Both countries, but especially Germany, have a large certified forest area. In fact, out of a forest area of 10 982 013 ha, 68 486 ha of Italian forests are FSC certified, while 881 854.43 ha are PEFC certified. In the case of Germany, on the other hand, out of a total of 11.4 million ha of forest, 8 700 643 ha are PEFC certified, and 1 421 457 ha are FSC certified.

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Data collection. The forest owners and managers involved in the survey were identified from the FSC and PEFC international databases, selecting the 'Forest management' option to include SFM certification holders. In the case of Italy in particular, the number of certified companies/bodies is 133, respectively 47 for PEFC and 86 for FSC (although, in reality, the latter number also included those involved in group certification). From the 133 entities contacted, 83 complete questionnaires were received, with a response rate of 62.4%. For Germany, there were 271 certified entities in the FSC database, but, as in the case of Italy, this number also included owners within the group certification. Taking account of the difficulty of finding the contact details of some owners, especially in the case of private individuals, a group of 55 entities was considered (without considering all other entities within the same group certification). In the case of PEFC certification, considering the high number of certified entities, approx. 12 000, following the methodology applied by Jaung et al. (2016a) and Krause and Matzdorf (2019), a sample of 400 entities was examined, using a simple randomisation sampling method, and received 71 completed questionnaires with a response rate of 15.60%. The development of the survey was based on the methods recommended by Dillman (2007), which include an information phone call (in the case of Italy), a pre-notification email, and a first and second email to maximise the response rate. Data were collected between August and December 2021.

The survey was conducted using a structured questionnaire in Google Forms, which in the case of Germany was translated into German, after having pre-tested a sample of eight Italian companies through the administration of the questionnaire through telephone interviews.

Survey. The questions in the questionnaire aimed to obtain information of a mainly quantitative nature and were formulated according to a closed or hierarchical response scheme. The questionnaire was structured in four sections and was preceded by a cover letter in which the title and objective of the research was stated, highlighting the importance of obtaining the requested information as well as the processing of the collected data.

In the first section, 'General characteristics of the company/entity and forestry certifications adopted', aspects relating to the entities interviewed were noted, such as: name; location; legal form; the type of ownership; the total area wooded and the certified forest area in ha; the type of forest species present; the main production that constitutes the core business; the number of employees; main product destination markets; main sales channels; average company turnover in euro; the types of certification adopted and the year of adoption. The second section, 'Characteristics of the forest owner/manager', provided information on the profile of the interviewees, specifically on age, educational qualification and gender, years of experience in the forestry sector. These data are reported in Table S1 in the Electronic Supplementary Material (ESM).

In the third section 'Perception of certification as a tool to support ecosystem services' the perception of forest owners/managers regarding the role of forest certification in guaranteeing ecosystem services was surveyed. Based on the study by Paluš et al. (2021) and the CICES classification [Common International Classification of Ecosystem Services (Haines-Young and Potschin 2012)], three groups of ecosystem services, 'provisioning', 'cultural' and 'regulating', were taken into account and sixteen items were identified. A 5-point Likert scale (Likert 1932) was used for the responses, where a score of 1 corresponds to 'completely disagree' and a score of 5 to 'completely agree'.

In the last section, 'Factors influencing the adoption of certification for ecosystem services', intentions, subjective norms, perceived behavioural control, attitudes, reasons for and against, i.e. the factors underlying BRT, were explored in 29 items. The items for the study constructs were again based on adapted versions of already validated scales (Westaby et al. 2010; Thompson, Hansen 2013; Krause, Matzdorf 2019; Sreen et al. 2021). In particular, the classification proposed by Claudy et al. (2015) and Dhir et al. (2021) into 'financial', and 'environmental' for reasons for and into 'barrier and cost', and 'incompatibility' for the reasons against was used. The scale used was set considering the same parameters as the one adopted in the previous section.

Data analysis. The statistical analysis was developed using SPSS software (Version 25, 2017), and Stata (Version 17, 2021). In the first step, a univariate descriptive analysis of the surveyed variables was carried out, including averages and standard deviations, for Likert scale responses to assess perceptions of certification as a tool to support ecosystem services. Regarding the application of BRT,

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data were analysed using SPSS 25 software for confirmatory factor analysis (CFA) to validate the measurement model, while the application of structural models (SEM) was used to assess the relationships between the component latent constructs of the basic conceptual model. They represent a multivariate statistical analysis technique that allows the consistency of the hypothesised model to be checked against empirical data (Barbaranelli, Ingoglia 2013). Such structural models are based on the implementation of path analysis on observed variables (i.e. those variables that are obtained by summing up, for example, items that make up a scale). Mplus 8 software (Mplus 8.7, 2021) was used to construct the SEM model. Two models were constructed: the first considering 'country' as the control variable, the second with a multigroup analysis considering the German and Italian samples separately. To check the fit of the model, following Bartolo et al. (2019), several statistical indices were considered, whose adopted cut-offs are made explicit in the brackets: chi-squared with its associated P-value ($P > 0.05$), the comparative fit index ($CFI \geq 0.95$), the root mean square error of approximation ($RMSEA \leq 0.06$) and its 90% confidence interval, the standard mean residual ($SRMR < 0.08$). The results of the confirmatory factor analysis with principal axis factoring and direct oblimin rotation considering factor loadings with a cut-off value of 0.30, included the Kaiser-Meyer-Olkin (*KMO*) test value, the Barlett test results and the explained variance. The *KMO* provides an index to compare the magnitude of the observed correlations against partial correlations. The closer its value is to 1, the better the evaluation of the results. Values below 0.60 are considered poor/not acceptable, i.e. factor analysis is not advisable. Barlett's test is used to assess the homogeneity of variance and must return a P-value of 0.01.

RESULTS AND DISCUSSION

Analysis of the perception of forest certification as a tool to support ecosystem services. Here the perception of owners and managers towards the role and positive effects that forest certification can have in ensuring the availability of forest ecosystem functions and services was analysed. Based on the existing literature in this research area (Haines-Young, Potschin 2012; Vizzarri et al. 2015; Ramanzin et al. 2019; Paluš et al. 2021; FSC Italia 2021a), ecosystem services have been classified into three macro-categories: 'provisioning and availability', 'regulating and maintenance' and 'cultural'. The reliability of the factors was examined using Cronbach's α coefficient. For Italy, a value of 0.95 was obtained, and for Germany a value of 0.96. For both Italy and Germany, the macro-category with the highest average value is 'regulation and maintenance' with values of 3.73 and 3.50, respectively. It is followed, for both countries, by the category 'cultural' with a score of 3.60 for Italy and 3.12 for Germany (Figure 2.). Specifically, the item that has the highest average value for both countries is represented by 'biodiversity conservation' with an average value of 3.96 for Italy and 3.86 for Germany, followed by 'the regulation of climatic conditions through the reduction of greenhouse gas concentrations and through carbon storage' in the Italian case with a value of 3.95, and 'maintaining the health of ecosystems' with a value of 3.77 in the German case (Table S2 in the ESM). These results show that forest owners and managers see certification as a tool to support regulating and maintaining ecosystem services. Indeed, in this context, both the principles and criteria of both certification schemes aim precisely at managing these aspects in a sustainable manner [an example is the high conservation values (HCV) promoted by FSC in principle 9, or criteria 1 and 2 on the maintenance and improvement of forest resources and the maintenance of the health and vitality of ecosystems promoted by PEFC]. These results differ from those obtained by Paluš et al. (2021), according to whom forest certification was seen as an excellent tool to support the availability of water resources and woody biomass. This can be explained by the fact that many ecosystem services forests are complex in nature and highly site-specific (Bösch et al. 2018). Other studies confirm the results of the present case. Jaung et al. (2016b), examining key FSC stakeholder adaptability to the incorporation of forest ecosystem services (FES), highlight high adaptability for biodiversity conservation.

Intentions towards the adoption of certification for ecosystem services. To understand which factors most influence the intentions of forest owners and managers towards the adoption of certification for ecosystem services, structural equation models were applied. This approach made it possible to verify the suitability of behavioural reasoning theory (BRT) for predicting respondents'

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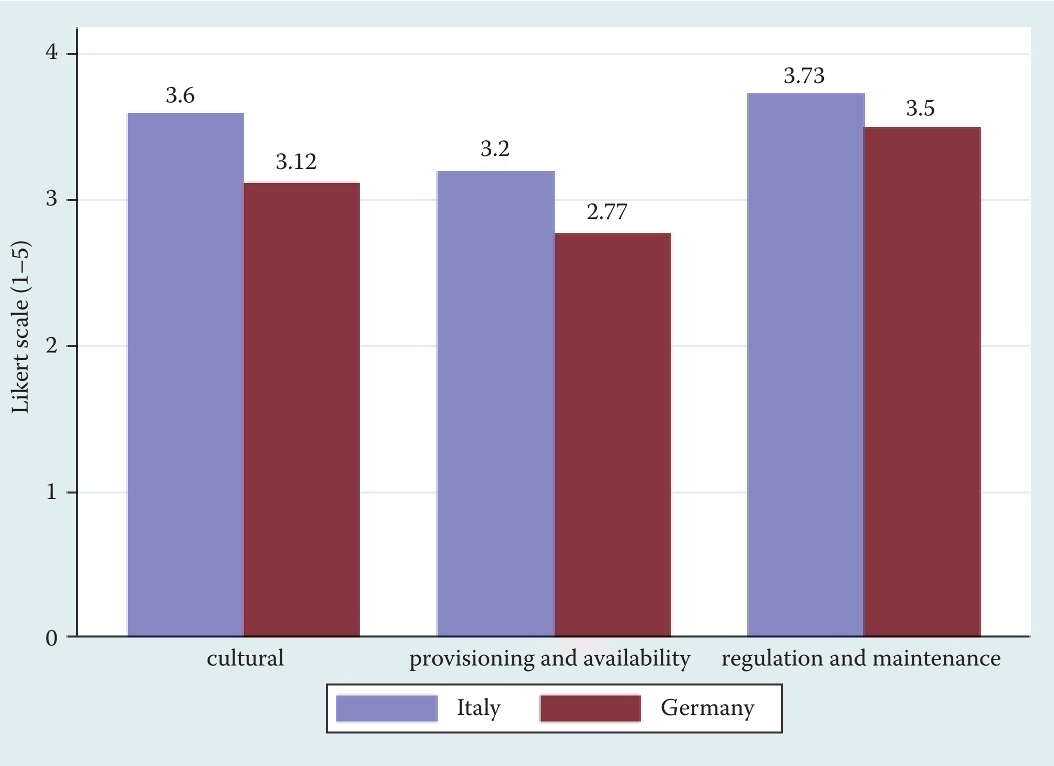

Figure 2. Analysis of the perception of forest certification as a tool to support ecosystem services

intentions, and thus assess the cause-effect relationships between the various constructs. Prior to the development of the path model, descriptive parameters were considered for the items analysed, such as the mean, standard deviation and Pearson correlations between latent variables (Tables S3 and S4, in the ESM), together with some fundamental components of construct reliability, i.e. *KMO* values, explained variance, Cronbach's alpha values (Table S5 in the ESM). Particularly for Intentions, most respondents were 'interested in evaluating the various opportunities that may arise from the certification of ecosystem services' (Table S3 in the ESM). Furthermore, the Attitudes and Reasons for 'financial' and 'environmental' and Subjective Norms were strongly correlated with Intentions (see Table S4 in the ESM).

For what concerns structural models, a model was initially constructed with the country as the control variable, a dummy variable where Germany was coded with 0 and Italy with 1, according to previous studies (Kumar et al. 2021; Yang et al. 2021). In addition, the hypotheses considered for BRT also explore the mediating effect of certain variables on intentions specifically attitudes, subjective norms, and perceived behavioural control. As regards the control variables, as shown in Figure 3, the significant effect ($P < 0.01$) of this variable is exerted only on subjective norms. Italian forest owners and managers are less influenced by subjective norms ($\beta = -0.20$); the β coefficient indicates how much the latent variable has a greater incidence if one comes from Italy. In fact, this coefficient assesses the effect of the latent exogenous variable, assuming values close to zero when this effect is weak and close to 1 or –1 when the effect is strong (Gamel et al. 2022). It can also be stated that attitudes ($\beta = 0.67$), reasons for 'financial' ($\beta = 0.12$) and perceived behavioural control ($\beta = 0.10$) have a direct and positive effect on intentions ($P < 0.01$), therefore hypotheses H_2, H_3, H_4 are accepted. In contrast, subjective norms have a less significant effect on intentions ($\beta = 0.07$, $P < 0.05$); therefore, hypothesis H_1 can only be accepted partially. Furthermore, reasons for 'environmental' have a greater influence on attitudes and perceived behavioural control than reasons for 'financial', but they indirectly influence intentions ($\beta = 0.22$, $P < 0.05$), thanks to the mediating effect played by attitudes, norms and control. In any case, hypothesis H_6, i.e. that reasons for positively influence the attitudes, subjective norms

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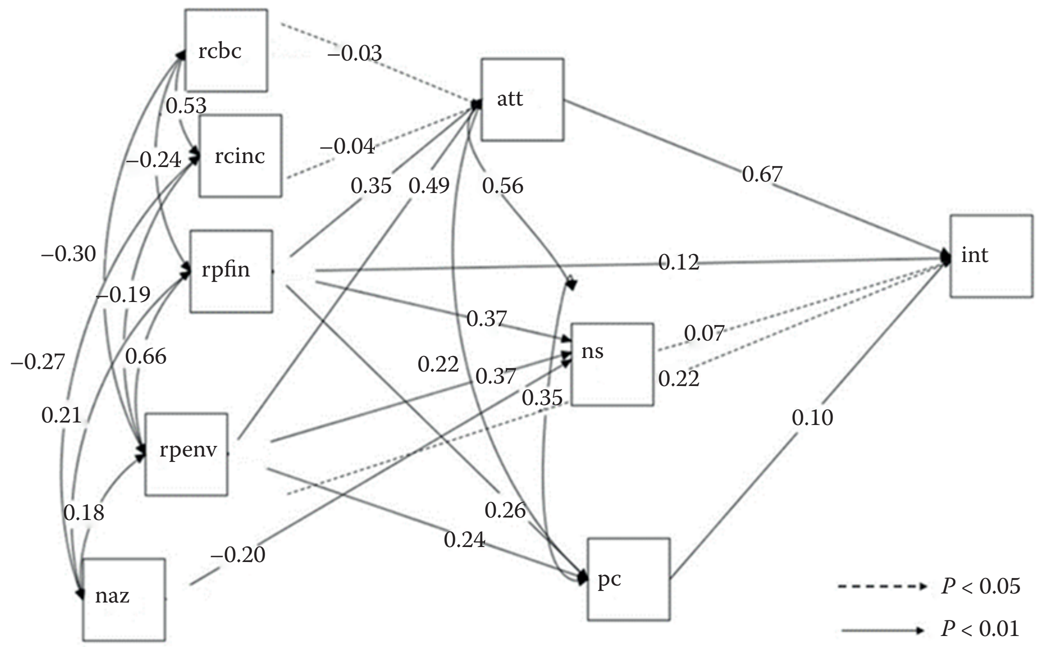

Figure 3. SEM model with control variable 'country' (naz, in the model)

SEM – structural equation model; rcbc – reasons against (barrier and cost); rcinc – reasons against (incompatibility); rpfin – reasons for (financial); rpenv – reasons for (environmental); naz – country; att – attitudes; ns – subjective norms; pc – perceived behavioural control; int – intentions

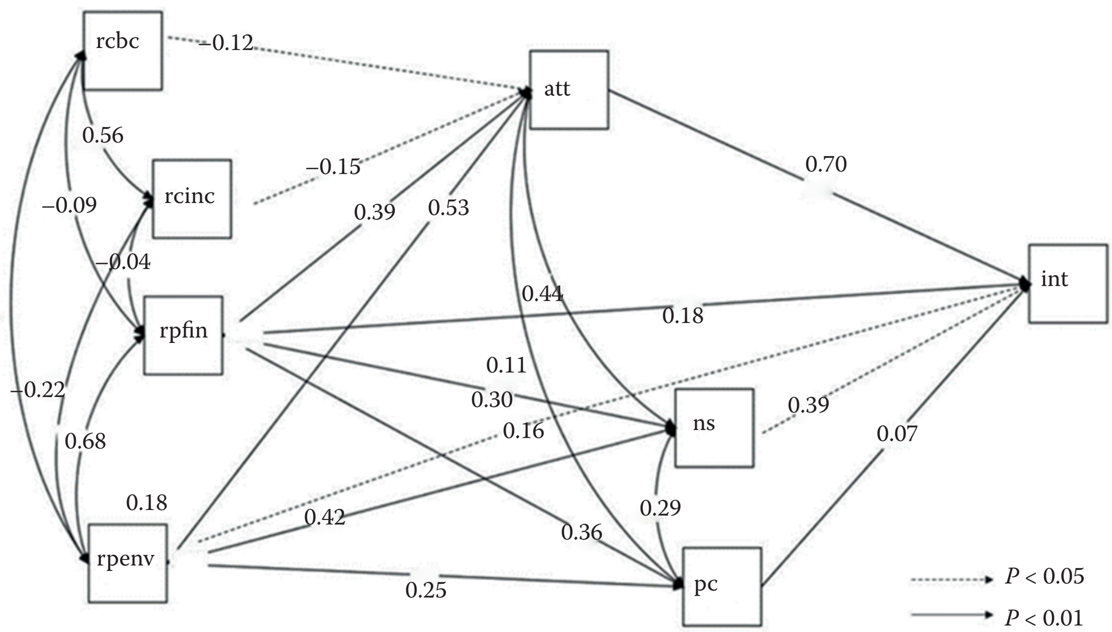

Figure 4. Multi-group SEM model for the Italian sample

SEM – structural equation model; rcbc – reasons against (barrier and cost); rcinc – reasons against (incompatibility); rpfin – reasons for (financial); rpenv – reasons for (environmental); naz – country; att – attitudes; ns – subjective norms; pc – perceived behavioural control; int – intentions

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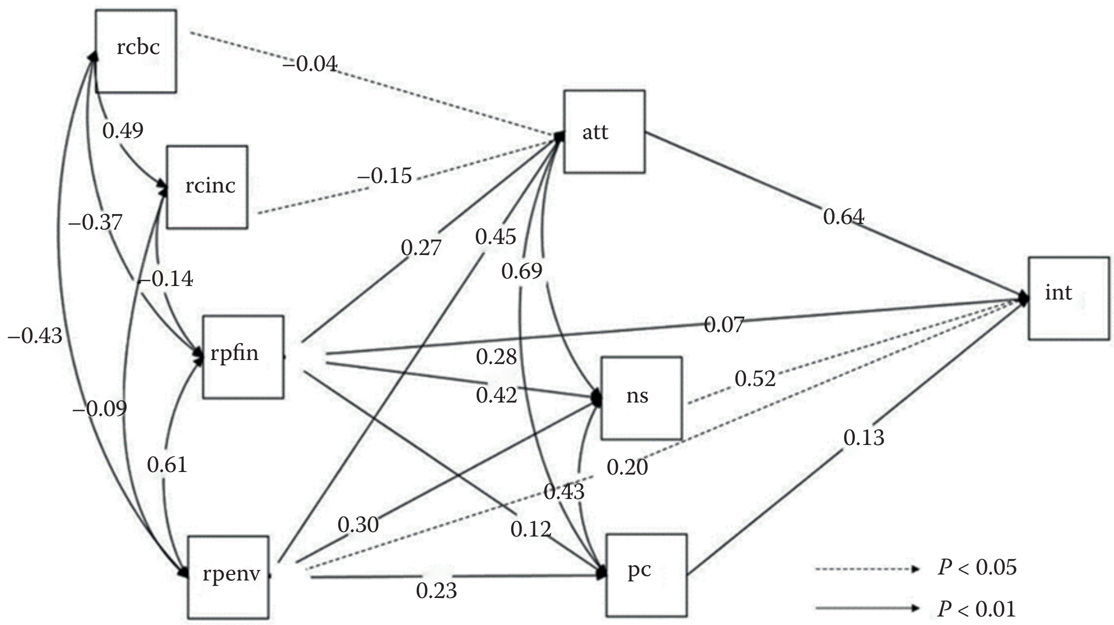

Figure 5. Multi-group SEM model for the German sample

SEM – structural equation model; rcbc – reasons against (barrier and cost); rcinc – reasons against (incompatibility); rpfin – reasons for (financial); rpenv – reasons for (environmental); naz – country; att – attitudes; ns – subjective norms; pc – perceived behavioural control; int – intentions

and perceived behavioural control, is accepted. Conversely, reasons against influence attitudes less significantly ($P < 0.05$), while they have no significant effect on intentions, norms and behavioural control; therefore, hypotheses H_5 and H_7 are rejected. However, the results show an adequate fit of the model (chi-squared with $P = 0.92$; $CFI = 1.00$; $RMSA = 0.028$; $SRMR = 0.022$).

Regarding the comparison between the two countries, in the Italian case, there is a lower correlation between reasons for and against (Figures 4 and 5). For example, while for Italy, the correlation between reasons against 'barrier and cost' and reasons for 'environmental' registers a value of –14, the same comparison for Germany stands at –43. Regarding the influence of attitudes on intentions, the comparison between the two countries shows a higher value in the Italian case, where attitudes have a greater influence on intentions, with $\beta = 0.70$. Also, for Italy, perceived behavioural control appears to have less influence than in German respondents who, on the other hand, recognise that they have the appropriate resources, skills and opportunities for the adoption of certification for ecosystem services. Regarding subjective norms, in both cases they were found to be insignificant on intentions ($P < 0.05$). This suggests that the social pressures represented by the very concept of a subjective norm (Gamel et al. 2022), being a voluntary certification related to SFM, are less relevant than the personal assessment of behaviour and the likelihood of its development represented by attitudes. In the case of reasons for, the effect of financial reasons on intentions is greater in the Italian sample. Finally, reasons against have little significant effect on attitudes, but are not found to be predictors of the other latent constructs and especially intentions. However, an adequate fit of the model is also found in this case (chi-squared with $P = 0.18$; $CFI = 0.99$; $RMSA = 0.059$; $SRMR = 0.043$).

CONCLUSION

This study aimed to analyse the intentions of Italian and German forest owners and managers to adopt certification for ES. To meet this goal, the theoretical framework of BRT was adopted. The results, in terms of analysing the role of certification as a tool to support ecosystem services, showed that respondents from both countries believe that certification can best support ecosystem services related to 'regulation and maintenance'

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and, in particular, the conservation of biodiversity. Through the application of BRT, on the other hand, the intentions of forest owners and managers towards the adoption of ES certifications were explored, thus verifying the soundness of the adopted theoretical model. Using the country as a control variable, it was observed that Italian forest owners are less influenced by subjective norms in the adoption of certification. Furthermore, attitudes, reasons for 'financial' and perceived behavioural control had a direct and positive effect on intentions, unlike subjective norms and reasons for 'environmental' that indirectly influence intentions. The reasons against were instead found to have no effect on intentions. The comparison between the two countries conducted in the multi-group model shows that attitudes have a greater influence on intentions in the Italian case, unlike perceived behavioural control, which has greater importance for German respondents. The latter recognise that they have the resources, skills, and opportunities to adopt certification for ES. In both countries, subjective norms have little effect on the intentions. The effect of reasons for, specifically of financial reasons on intentions, is greater in the case of Italy. In both countries, reasons against do not represent predictors of intentions. In both case studies, there is a good propensity to evaluate the various opportunities that may arise from the certification for ES. The results, therefore, only partially confirmed the usefulness of this model to explain the psychological factors that drive owners towards the adoption of ES certifications. In fact, while some assumptions concerning the TPB were fulfilled, others relating to its extension, and in particular to the influence of the reasons against on intentions were not. In any case, attitudes and reasons for had a significant influence on intentions. Therefore, the intentions to adopt certifications for ES are explained by the attitude towards the adoption of such certifications. These results could have interesting implications for policymakers who can focus on the diffusion of certification of ecosystem services by trying to support the attitudes, and reasons for 'financial and environmental' expressed by forest owners and managers towards the intention to adopt such certification through eco-policies. Especially for Italian forest areas, which are almost always not exclusively productive, forest certification, and more specifically certification for ecosystem services, could translate into an improvement in forest management, starting from the very fact that it makes management plans compulsory. However, the study has some limitations due mainly to the number of respondents, a total of 154 (71 for Germany and 83 for Italy), which, particularly in the case of Germany, is an unrepresentative number, considering the large number of certified companies. Furthermore, unlike in the case of Italy, it was not possible to conduct telephone interviews for this sample. However, it should also be pointed out that the study is based on companies, and not individuals, so as Tenenhaus et al. (2005) stated: 'there can be more variables than observations and there may be a small amount of data that are missing completely at random'. Finally, only two European countries were involved in the study, one of them being Germany where certification standards for ES are still being developed (Seizinger 2021). With this in mind, it might be interesting to conduct other cross-country studies involving other countries in order to compare the results obtained and verify the adaptability of the theoretical model adopted to new geographical scenarios.

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