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Assessing Spatial and Temporal Changes of Natural Capital in a Typical Semi-Arid Protected Area Based on an Ecological Footprint Model

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Abstract: Exploring spatial and temporal changes in protected areas (PAs) is essential for protecting natural capital and creating a harmonious relationship between humans and nature. This study has assessed land use/land cover (LULC) changes in the Jajrud, a Protected Area with a semi-arid climate zone in Iran (covers an area of 18,814 km^2), to assess the sustainability of the use of natural resources using Landsat imagery from 1989 to 2018. Likewise, Ecological Footprint accounts (including the sum of biological, freshwater, energy, and pollution) and changes in the per-capita Ecological Carrying Capacity were investigated to uncover Ecological Deficits. The Ecological Pressure Index was used to explore driving factors of natural capital utilization in each of the various identified zones. Between 1989 and 2018, high-density pastures decreased the most in Jajrud, while built-up land increased the most. Likewise, the Ecological Footprint increased while the Ecological Carrying Capacity decreased, increasing Ecological Deficit quantities. Driving factors for the use of natural capital differs among the various zones due to differing management goals, type of uses, and human activity development. As supply and demand for natural resources were clearly out of an imbalance between the supply and demand of natural resources and exceeded the maximum tolerable limits in Jajrud, a change in production and consumption patterns is necessary. This case study has practical importance for establishing mathematical models to reveal the patterns of LULC, ecological footprint, ecological deficit, and ecological pressure indices in a typical PA in a semi-arid region of Iran. Our approach is advisable for semi-arid PAs in Iran and regions with similar attributes in other countries.

Keywords: ecological footprint; ecological carrying capacity; Jajrud protected area with the sustainable use of natural resources; Tehran province; Iran

1. Introduction

Natural capital includes natural resources and environmental services in pristine and natural ecosystems that play an important role in human well-being and sustainable development [1,2]. However, changes in natural systems may threaten and destroy this valuable natural capital [3]. Therefore, exploring trends of spatial and temporal changes in natural capital assists with assessing ecosystem functioning and the levels of sustainable development of Protected Areas (PAs) [4,5]. PAs are recognized as natural capital [6]. Given the vital role of PAs in the conservation of biodiversity and natural capital [7], spatial and temporal changes need to be monitored that may impact conservation goals, in light of increasing pressure from human activities [8,9]. The protection of natural capital is essential for human survival, the preservation and availability of environmental services, and the realization of sustainable development goals [10]. Increasing pressures on PAs have led to decreased natural capital and threatened habitats [11].

Accordingly, in the 1990s, the Ecological Footprint (EF) concept was proposed to measure sustainability. This concept provides a valuable holistic tool for assessing sustainability [12] and examines the impacts of human activities on natural environments [13]. As a well-known composite model of sustainability, the EF measures human demand in nature by assessing biological production and the use of land [12,14]. It captures the use of natural resources, such as water areas, cropland and garden, grasslands, and built-up areas [15]. EF is measured in terms of weight per hectare (bio-productivity) or global hectares (gha), and assesses different land uses [16]. Relatedly, the concept of Ecological Deficit (ED) measures the extent to which the footprint of a population exceeds the Ecological Carrying Capacity (ECC) of an area available for human use.

For instance, Li et al. [17] quantitatively assessed the physical value of natural capital in China based on an EF model. Between 2000 to 2018, physical quantities of the per-capita EF and per-capita ED increased, while the physical quantity of per-capita ECC decreased. Zhang and Zhu [18] studied the temporal and spatial variability of the carrying capacity of water and land resources in Beijing, China. The results indicate that the use of these resources is out of balance in half of the cities in their study area, so improving the resource management system and changing production and consumption methods are recommended to promote ecologically sustainable development. Long et al. [19] studied sustainability based on a three-dimensional EF and human development index. The results demonstrate that the studied areas face an ED and increasing the human development index by reducing the EF can improve the efficiency of ecological resource use and achieve sustainable urban development in these areas. Wu et al. [20] studied the sustainability and decoupling effects of natural capital use in China by also employing three-dimensional EF. The results illustrate that an environmental surplus occurred in 2000, while all provinces were in a state of ED in 2016. In addition, EF per capita increased due to an increase in croplands and built-up land areas. Cohen et al. [21] reviewed the previous literature on the degree of substitutability between natural capitals vs. other forms of capitals and found that most available substitutability estimates do not stand up to scrutiny. Galli [22] evaluated the EF across six municipalities in Portugal and found that EF accounting can be used to support local strategies and reach Sustainable Development Goals (SDGs) targets.

Despite the importance of PAs as major conservatories of natural ecosystems, not enough attention has been paid to studying changes in natural capital and biodiversity [23,24], especially for arid and semi-arid areas with ecological resource shortages [25]. The present study contributes to addressing this gap by examining spatial and temporal changes in natural capital in the Jajrud, a PA in Iran. The area has great value due to its high biological richness and many natural, historical, and cultural sights and attracts large numbers of tourists daily. In recent years, the Jajrud has experienced a significant loss in biodiversity and threat to habitats due to increasing urbanization and the impacts of human activities from the metropolis of Tehran. Multiple factors are contributing to these issues, including illegal activities, the development of various physical and economic activities, lack of sufficient monitoring, the establishment of industrial sites, overexploitation of mines, specific infrastructures, the expansion of transport networks and roads, and the development of tourism activities [9,26].

The assessment of the current status of natural capital is not only the basis for regional ecological construction evaluation but also an important indicator of the effectiveness of regional sustainable development strategies. Therefore, we asked four main questions in our research: (1) What are the land use/land cover changes (LULC) in the Jajrud Protected Area between 1989 and 2018? (2) How is the per-capita EF and ECC status in the studied years? (3) What is the Ecological Pressure Index (EPI) value? (4) What factors affect natural capital in the identified zones and the EPI? To answer these questions, we propose an EF model to measure the pressures of human activities on natural capital in the Jajrud. We based the EF model on national average production from 1989 to 2018, when human activities and urban development increased the most. Likewise, natural capital consumption in this area was analyzed across these years. Dynamic changes in the per-capita ECC were also investigated. Finally, the EPI [27] was used to examine factors affecting natural capital utilization in the study area.

2. Materials and Methods

2.1. Study Area

The Jajrud Protected Area is located in the Tehran Province (Figure 1). The Tehran Province, with the capital of Tehran city, covers an area of 18,814 km^2 in the north of Iran [28]. It is located between the latitudes 34° and 36.5° N and the longitudes 50° and 53° E [29]. The climate of the Tehran province is semi-arid (northern part) to arid (southern part), with a mean annual precipitation of 250 mm and a mean annual temperature of 17.0 °C [30]. The dry season lasts for four months [29]. This PA was chosen among other Tehran PAs due to the rapid population growth, increasing urbanization, obvious LULC changes, and uncontrolled development of human activities. With a size of about 74,811 ha, this is one of the largest PAs in the Tehran province. The Jajrud encompasses two unique national parks of high biological richness, including the Khojir and the Sorkheh Hesar. The highest mountain in the area is Araku, with an altitude of more than 2600 m above sea level. This area is the main habitat of wild sheep (*Ovis orientalis*), and 517 vascular plant species and 29 major plant groups have been identified [9,26].

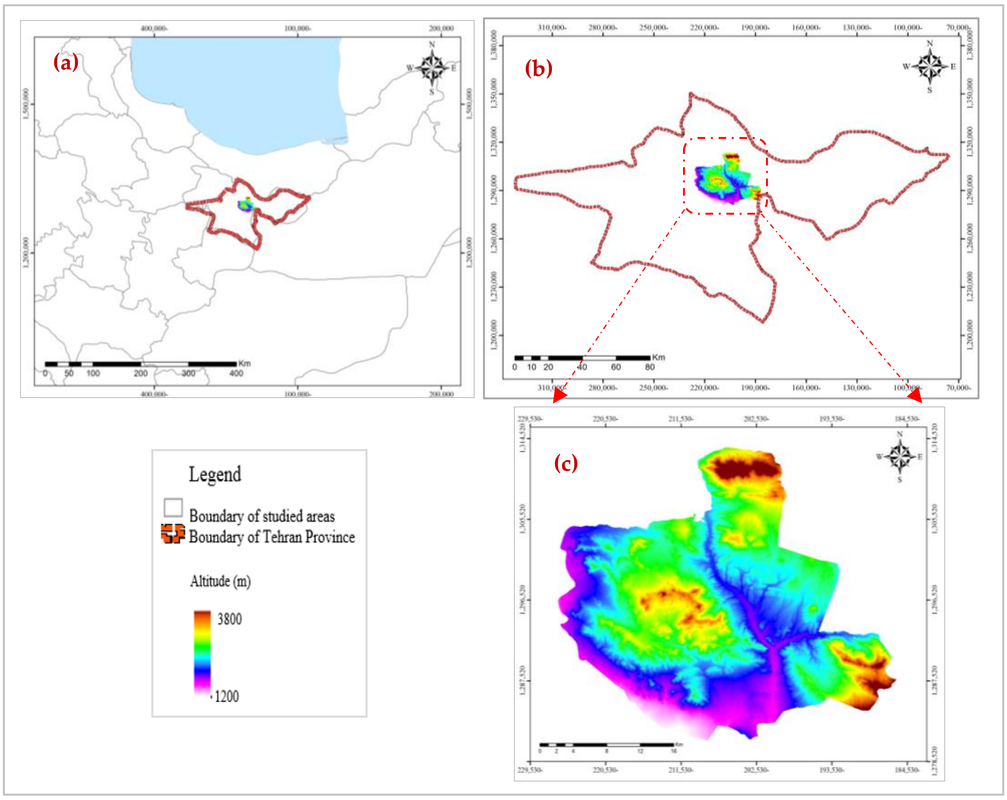

Figure 1. Location of the study area in (**a**) Iran, (**b**) Tehran province, (**c**) the "Jajrud Protected Area with the Sustainable Use of Natural Resources".

2.2. Methods

2.2.1. EF Model

The EF model depends on the local economies' production level, total population, and the level of urban development. The calculation of this model is performed to convert various consumed resources in relation to the corresponding bio-productive land area. On the other hand, the EF model balances and simplifies the supply-demand of biological production space in complex ecological and economic processes [31]. In addition, the calculation of ECC depends on natural factors, such as the region's geographic location, precipitation, land conditions, etc. [18,32].

Measurement Unit

The global average yield is determined for the assessment of the EF in global units per hectare (gha) because it specifically refers to the yield of biological products per global unit area. The gha represents hectares with the potential to produce usable biomass equal to the world's potential average of that year [33]. For this purpose, the average global production is calculated using Equation (1).

$$\mathrm{Epj} = \mathrm{pj}/\mathrm{sj} \tag{1}$$

where Ep_j: the average global yield, p_j: global yield, and s_j: global productive area of the biologically productive resources in category j.

2.2.2. EF Account

EF in this area includes the sum of the bio-ecological footprint (EF_B), freshwater ecological footprint (EF_W), energy ecological footprint (EF_E) and pollution ecological footprint (EF_P). Likewise, EF accounts are calculated using Equation (2), and EF per capita (ef) is obtained from Equation (3).

$$EF = EF_B + EF_W + EF_E + EF_P \tag{2}$$

$$ef = EF/N \tag{3}$$

where N is representing the total population.

2.2.3. Biological Resource Account

The biological resources account (BRA) is derived from the EF generated by the consumption of various biological resources, such as cultivated land, forest land, grassland and water area. The formula is in Equation (4).

$$EF_B = \sum[r_i \cdot \sum_j (c_j/ep_j)] \tag{4}$$

where EFB is the EF of biological resources, r_i is the equivalence factor, c_j is the consumption of type j of biological resources, and ep_j is the national average output of the accounting items in category j.

2.2.4. Freshwater Account

The freshwater account represents agricultural water, industrial water, domestic water, and ecological water. It is worth noting that water resources are evenly distributed over a certain area [34]. The EF_W is calculated using Equation (5).

$$EF_w = r_{water} \cdot \sum_{j=1} \cdot (w_j/p_w) \tag{5}$$

where EF_W is the EF of freshwater, r_{water} is the equivalence factor of the water area, w_j is the total water consumption in water-use category j, and p_w is the national average production capacity of the water resources.

2.2.5. Energy Consumption Account

The energy consumption account is calculated from the sum EF of the regional electricity consumption and fossil fuel combustion:

$$EF_E = EF_{built\text{-}up} + EF_{fossil\text{-}fuel} = ec/ep \cdot r_{built\text{-}up} + f \cdot (1 - S_{ocean})/\omega \cdot \mu \cdot r_{forest} \tag{6}$$

where EF_E includes $EF_{built\text{-}up}$ (i.e., the EF of energy), $EF_{fossil\ fuel}$ (i.e., the EF of energy use), ec (i.e., the total regional power consumption), and ep (i.e., the power that can be provided per unit area of built-up land, with a value of 4.66×105 kW·h/ha) [35]. Likewise, $r_{built\text{-}up}$: the equivalence factor of built-up land, f: the total regional CO_2 emissions, S_{ocean}: the proportion of oceans that absorb CO_2 from global human emissions, ω: carbon sequestration factor, μ: carbon and carbon dioxide conversion rate, r_{forest}: the equivalence factor of forest land, with values of S_{ocean}: 0.281, ω: 097 and μ: 0.27 [36].

2.2.6. Environmental Pollution Account

The environmental pollution account is used to calculate the area of land required to absorb pollutants produced in the area, which is obtained from the ratio of pollutant discharge volume to the average absorption capacity of the relevant land type. In the present study, the environmental pollution account includes chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) for water pollutants, sulfur dioxide (SO_2) and NO_x for air pollutants, and solid waste for solid pollution [2,17]. The formula is presented in Equation (7).

$$EF_P = \sum (u_i/e_i) \tag{7}$$

where EF_P: the EF of pollution, e_i: the purification coefficient of the natural ecosystem for category i, and u_i: the sewage per unit area of water.

2.2.7. Ecological Carrying Capacity (ECC)

The ECC is understood here as the total area of bio-productive land that can provide for the development of human society. The formula is presented in Equation (8). The ECC per capita is calculated using Equation (9):

$$ECC = (1 - 12\%) \times \sum_{i=1} (a_i \cdot r_i \cdot y_i) \tag{8}$$

$$ec = ECC/N \tag{9}$$

where; a_i: the area of biologically productive land in category i, r_i: the equivalence factor, and y_i: yield factor of type i land. It is worth noting that biologically productive land includes cultivated land, forest land, grassland, water area, and construction land. In addition, the ECC calculations must follow recommendations given by the World Commission on Environment and Development [37], meaning 12% need to be subtracted to protect local biodiversity.

2.2.8. Value of the EF Account

The main components of the quantitative EF value (EF^v) include the value of the consumption of biological resources (such as agriculture, forestry, animal husbandry and fisheries), the value of freshwater consumption (such as the value of direct freshwater consumption), the energy consumption value (including electricity and fossil energy products) and the cost of pollution control (including the economic cost of treating major water pollutants, air pollutants and solid pollutants). Accordingly, the EF^v is calculated from Equation (10), and the EF^v per capita is calculated using Equation (11):

$$EF_V = EF_B{}^v + EF_W{}^v + EF_E{}^v + EF_P{}^v = \sum_i GDP_i + \delta \cdot w + \sigma \cdot e + \beta \cdot \sum_j (c_j \cdot d_j) + \sum_k (r_k \cdot u_k) \tag{10}$$

$$Ef_v = EF^V/N \tag{11}$$

where $EF_B{}^v$: the value of biological EF, $EF_W{}^v$: the value of freshwater EF, $EF_E{}^v$: the value of energy EF, and $EF_P{}^v$: the value of the pollution EF. Likewise, GDP_i is the gross domestic product output value of category use i (such as planting, animal husbandry, forestry and fishery), and δ is the average water supply price. Moreover, w: annual electricity consumptions, e: annual water consumptions, φ: the electricity price, β: the unit standard coal price, c_j: consumption coal and fossil energy, d_j: standard coal conversion coefficient and fossil energy in category j, u_k: the emission amount of pollutant type k, and γ_k is the treatment cost of pollutant type k.

2.2.9. Value of the ECC

The ECC represents the supply of natural capital, social, economic, and human activities in the ecosystem, and the annual ecosystem services budget [38]. Therefore, the value of ecosystem services can be used to calculate the ECC^v. The formula is presented in Equation (12).

$$ECC^V = N \cdot ec^v = \sum_i (V_i \cdot ECC_i) = \sum_i [ECC_i \cdot (ESV_i / EQF_i)] \tag{12}$$

where ES_{Vi} is the value of ecosystem service per unit area of land in category i, of which the formula is presented in Equation (13).

$$ESV_i = D_i \cdot F_i = 1/7 \sum_{j=1} (m_j \cdot p_j \cdot q_j / M_t) \cdot \sum_k e_{ik} \tag{13}$$

The ec^v per capita is calculated using Equation (14)

$$ec^V = ECC^V / N \tag{14}$$

In this study, V_i: the price, ECC_i: ecological carrying capacity and EQF_i are the conversion factors of the land in category i. Moreover, D_t: the ecosystem service value of a standard equivalent factor in year t, j: the type of food crop and m_j, p_j, and q_j indicate the sowing area, price, and unit-area yield of a food crop in category j, respectively. In these expressions, M_t: total sowing area of n kinds of food crops in year t, F_i: the sum of equivalent factors of ecological service values of type i land, and e_{ik} is the equivalent factor of type k ecological services type i land.

2.2.10. ED Calculation

The ED determines the extent to which the amount of natural capital in the area meets consumer demand. Accordingly, if ECC < EF, then ED < 0, indicates an ecological deficit in the area. The ED is calculated using Equation (15), and the formula for ED per capita is presented in Equation (16).

$$ED = ECC - EF \tag{15}$$

$$ed = ec - ef \tag{16}$$

where ECC and EF are physical quantity values, and ED explains the ecological deficit of these values.

2.2.11. Determining Ecological Pressure Index (EPI)

The EPI is the ratio of EF to ECC and determines ecological challenges and risks in the area. The EPI is calculated using Equation (17):

$$EPI = EF / ECC \tag{17}$$

2.2.12. Data Collection and Classify Images

To classify and assess the trend of LULC changes, maps from 1989 to 2019 were prepared using L5-TM (21 April 1989), L5-TM (21 April 1999), L7-ETM+ (21 April 2009), and L8 and OLI- TIRS (21 April 2019) from the United States Geological Survey (USGS). In this study, the Random Forest (RF) algorithm was used as a supervised method for classifying images [39]. This algorithm is a decision tree-based group learning method that combines regression trees and massive set classification [28,40]. To set this algorithm, two parameters are needed, including (1) the number of trees that can be explained by "n-tree" and (2) the many properties in each division which can be explained by "m-try" [28]. In addition, classification trees increase individual selection power and provide accurate classification in arranging votes of trees throughout the forest. After pre-processing and correcting satellite images, the LULC map of the "Jajrud Protected Area with the Sustainable Use of Natural Resources" was classified into built-up land, water body, cropland and garden, high-density pasture, low-density pasture, and planted forest. To classify, 600 samples were randomly generated from the satellite imagery for each class. The sample collection includes 300 samples for training and 300 samples for classification evaluation. Likewise, classification accuracy was evaluated using this study's confusion matrix and overall accuracy. The Normalized Difference Vegetation Index (NDVI) was also employed to distinguish vegetation from other kinds of cover [41]. Accordingly, the LULC of pastures was classified into high-density and low-density classes [42,43]. In addition, EF was calculated according to suggested data in Table 1 and based on a global system in gha.

Table 1. Data sources and details (Source: https://data.footprintnetwork.org, 17 December 2021).

Factors	Indicators
Biological account	- Agricultural products (such as cereal, beans, tubers, cotton, oil-bearing crops, fiber crops, tobacco, sugarcane, etc.) - Grass products (such as beef, lamb, milk, wool, cashmere and honey) - Forest products (such as wood, tea and garden fruits) - Aquatic products (such as shrimps, crabs and fish)
Freshwater account	- Total water consumption in agriculture, industry, living and ecology activities
Energy account	- Consumption of various energy and fossil fuels, including coal, coke, petroleum, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, natural gas and electricity
Pollution account	- Release of pollutants including COD, NH_3-N, SO_2, NO_x and solid waste
Prices of agricultural products	- The price of major farm products

3. Results

3.1. LULC Changes

This study assessed LULC changes using Landsat imagery from 1989 to 2018. As the results demonstrate, the overall accuracy of classification is high and acceptable in terms of efficiency (Table 2). According to Table 3 and Figure 2, the results illustrate that in the Jajrud, high-density pasture decreased the most from 39.08% (29,241 ha) in 1989 to 38.13% (28,528 ha) in 2018, while built-up land increased the most from 10.48% (7842 ha) in 1989 to 12.06% (9023 ha) in 2018. Cropland and gardens increased slightly from 2.30% (1724 ha) in 1989 to 2.32% (1742 ha) in 2018, and so did water bodies from 0.9% (676 ha) in 1989 to 0.94% (710 ha) in 2018. Planted forest decreased from 2.34% (1754 ha) in 1989 to 2.25% (1686 ha) in 2018, and low-density pasture also decreased from 44.87% (33,574 ha) in 1989 to 44.27% (33,122 ha) in 2018.

Table 2. Overall accuracy (OA) of the prepared map of land use and land cover (LULC) change from 1989 to 2018 in the Jajrud Protected Area with the Sustainable Use of Natural Resources, Iran.

Prepared LULC Map	Year			
	1989	1999	2009	2018
Overall accuracy	0.87	0.92	0.85	0.95

Table 3. Changes in land use and land cover (LULC) from 1989 to 2018 in the Jajrud Protected Area with the Sustainable Use of Natural Resources, Iran.

Classes	Year								Variation 1989–2018		Decreasing/ Increasing Trend
	1989		1999		2009		2018				
	Area										
	ha	%	ha	%	ha	%	ha	%	ha	%	
Built-up *	7842	10.48	7963	10.64	8332	11.13	9023	12.06	1181	1.58	+
Water body	676	0.9	681	0.91	698	0.93	710	0.94	34	0.04	+
Cropland and garden	1724	2.30	1738	2.32	1744	2.33	1742	2.32	18	0.02	+
High-density pasture	29,241	39.08	29,212	39.04	29,150	38.94	28,528	38.13	−713	−0.95	−
Low-density pasture	33,574	44.87	33,474	44.74	33,193	44.36	33,122	44.27	−452	−0.6	−
Planted forests	1754	2.34	1743	2.33	1694	2.26	1686	2.25	−68	−0.09	−
Sum total	74,811	100	74,811	100	74,811	100	74,811	100	—	—	−

* Note: Built-up lands = residential, commercial, industrial, and roads.

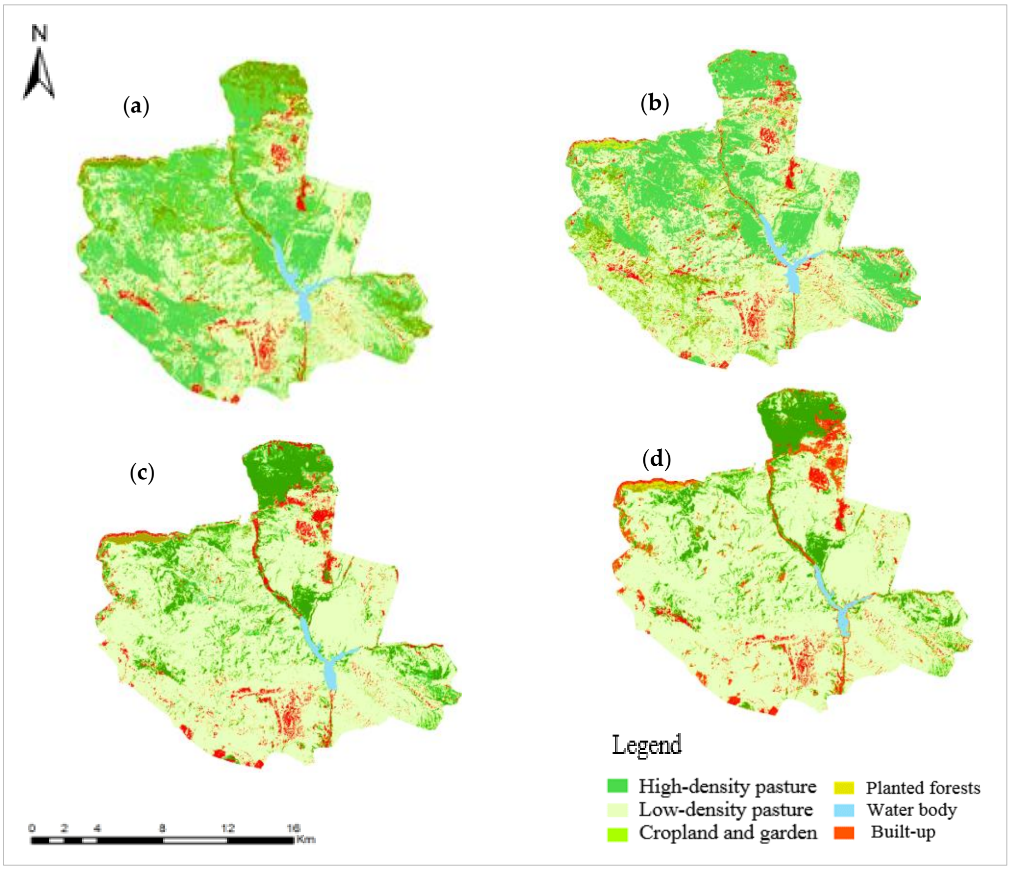

Figure 2. Land use and land cover (LULC) change maps of the Jajrud Protected Area with the Sustainable Use of Natural Resources, Iran for (**a**) 1989, (**b**) 1999, (**c**) 2009, and (**d**) 2018.

3.2. Dynamic Changes in EF, ECC, and ED Quantities

In the study area, EF increased from 1.5 gha in 1989 to 3.3 gha in 2018, while ECC decreased from 0.9 gha in 1989 compared to 0.7 gha in 2018 (Figure 3). ED also increased from −0.6 gha in 1989 to −2.6 gha in 2018. At the per-capita level, ef has risen from 1.38 gha in 1989 compared to 2.75 gha in 2018 (whit average annual = 4.23%), while ec has decreased from 0.56 gha in 1989 compared to 0.47 gha in 2018. As the results demonstrate, ed has also increased from −0.74 gha in 1989 to −2.12 gha in 2018.

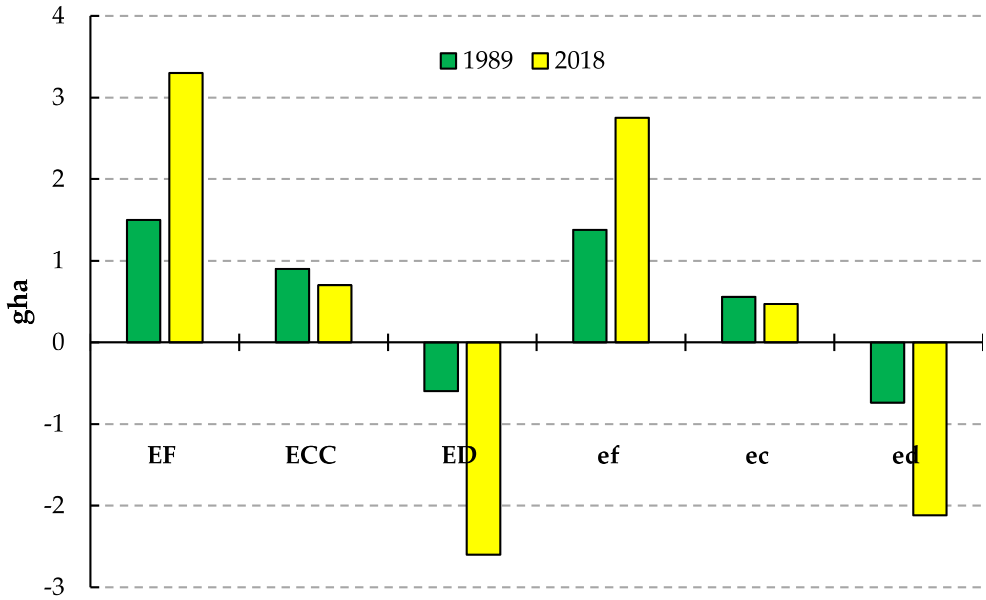

Figure 3. Change in EF, ECC, ED, ef, ec, ed in the Jajrud Protected Area with the Sustainable Use of Natural Resources, Iran.

3.2.1. EF, ECC and ED Value Changes (Total and Per-Capita Quantities)

As illustrated in Figure 4, EF, ECC, and ED values have increased from 1989 to 2018. Likewise, EFv has increased from 0.62 trillion US dollars in 1989 compared to 2.65 trillion US dollars in 2018. ECCv has also increased from 0.41 trillion US dollars in 1989 to 1.70 trillion US dollars in 2018, and the EDv has decreased from −0.34 trillion to −0.68 trillion US dollars in these years. The results of the per-capita values revealed that the annual ef^v has increased from 0.56 trillion US dollars to 1.78 trillion US dollars. Likewise, ecv has increased from 0.32 to 1.18 trillion US dollars, and edv has decreased from −0.25 to −0.58 trillion US dollars. Accordingly, the results indicate that ECC has increased due to nature conservation measures implemented over the study years.

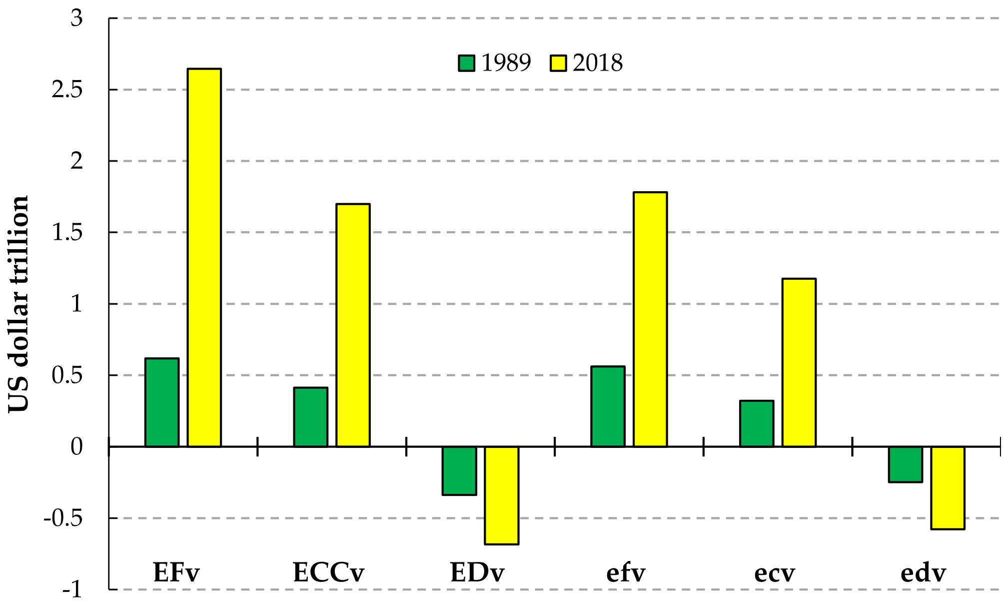

Figure 4. Change in value of EF, ECC, ED, ef, ec, and ed in the Jajrud Protected Area with the Sustainable Use of Natural Resources.

3.2.2. Analysis of the EF Value Quantities

According to Figure 5, due to the increase in the price of biological resource products and increased human demand, the highest total EFv applies to the EFB, followed by the highest value for the EFE. The total EFv ratio has increased from 34.87% in 1989 compared to 54.32% in 2018.

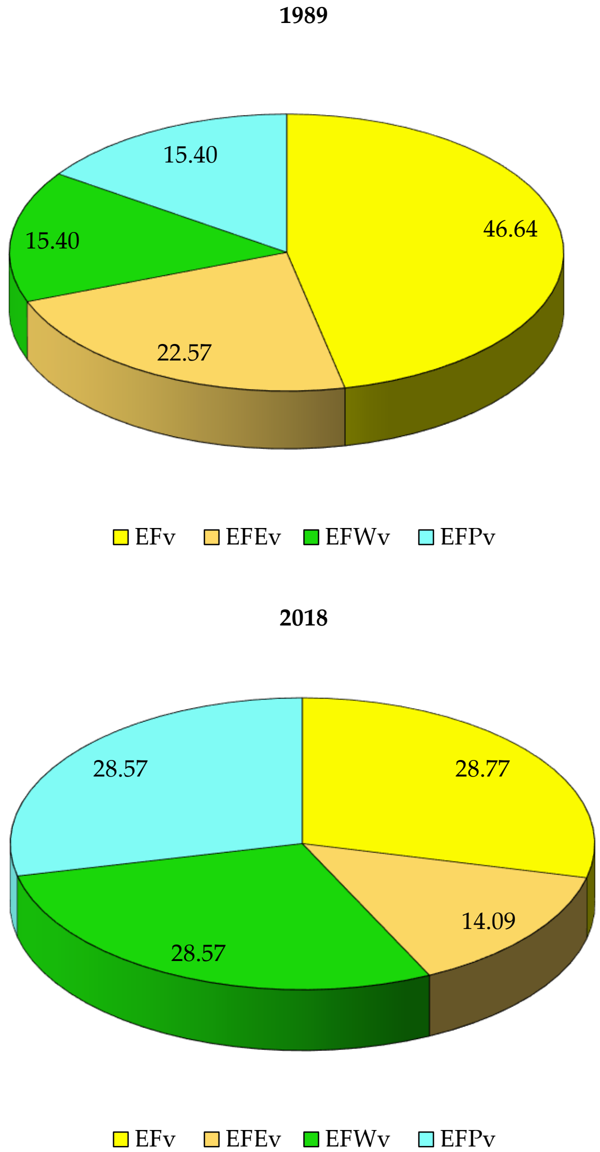

Figure 5. Proportions (%) of value quantities of EF in various accounts (1989 vs. 2018).

3.3. Examination of the EPI

The EPI^{v} in this area is 1.5, meaning that the Jajrud needed only 1.5 times more land area to meet the current development model. In addition, physical EPI was ranked 18th, while value EPI was ranked sixth. This result indicates that in this area, physical EPI is different from the EPI^{v}. Physical EPI represents an imbalance between the supply and demand of natural resources, while the EPI^{v} mainly reflects the ecological threat from ecological resource occupation. Hence, these differences explain that a physical or EF^{v} alone cannot reflect regional sustainable development accurately.

3.3.1. Investigation of Factors Affecting the EPI

In this study, factors affecting the EPI were investigated to assess factors driving natural capital utilization. As can be seen in Table 4, a list of factors affecting the EPI has been collated from a literature review of theoretical and empirical research and by soliciting expert viewpoints [2,17]. In this investigation, the physical (Y_1) and value (Y_2) EPI were considered dependent on factors influencing the level of natural resource consumption. These factors include natural capital, resource consumption, region size, economic development, and ecological construction; with the latter representing the interaction between nature and human construction. In addition, 12 indicators (X_1 to X_{12}) were defined as driving factors. This list was presented to experts to rate on a scale from 1 to 5. The per-capita ECC received the highest ratings with a value of 4.18 for natural capital, then for daily water consumption with a value of 2.88 related to resource consumption, and for the level of built-up areas with a value of 4 related to region size. The added value from industry received a value of 3.35 related to economic development, and recovered areas received a value of 3.26 related to the ecological construction factor.

Table 4. List of factors affecting the Ecological Pressure Index (EPI).

Factors Affecting	Driving Factors	Independent Variable	Value
Natural capital	Per capita ecological carrying capacity (nha)	X_1	4.18
Resource consumption	Daily energy consumption (10,000 tce)	X_2	2.67
	Daily water consumption (10,000 m^3)	X_3	2.88
Region size	Resident population (10,000 persons)	X_4	2.90
	Level of built-up areas (km^2)	X_5	4.00
Economical development	GDP per capita (US dollar)	X_6	2.84
	The added value of the industry (US dollar 100 million)	X_7	3.35
	Total sales of consumer goods (US dollar 100 million)	X_8	2.75
Ecological construction	Artificial afforestation areas (1000 ha)	X_9	2.90
	Recovered areas (1000 ha)	X_{10}	3.26
Scientific advancement	Investment in biodiversity conservation projects and control development activities as a percentage of GDP (%)	X_{11}	2.94
	Investment in science and research projects as a percentage of GDP (%)	X_{12}	3.00

3.3.2. Driving Factor Analysis per Identified Zones

The present study has investigated factors affecting ECC in each identified zone in the Jajrud (Table 5). This area encompasses nine zones which include a strict nature reserve (with an area of 15.11%), protected zone (32.88%), extensive use zone (1%), intensive use zone (0.02%), recovery zone (19.96%), special use zone (0.002%), buffer zone (10.26%), multiple-use zone (12.63%), and common protection zone (8.12%). According to Table 5, the factors that affect ECC the most in the strict nature reserve (0.80, 0.77), protected zone (0.88, 0.85), and the common protection zone (0.97, 0.94) relate to the per-capita ECC, the investment in biodiversity conservation projects and the control of development activities. In contrast, most driving factors in the extensive use zone (0.95) were related to investment in science and research projects. In the intensive use zone (1.28, 1.34) driving factors relate to daily energy and water consumption, while in the recovery zone (1.12, 1.10) they relate to artificial afforestation areas and recovered areas. In the special use zone (1.11) they relate to the level of built-up areas, and in the buffer zone (1.08, 1.02) they relate to recovered areas and investment in biodiversity conservation projects and control of development activities.

Finally, in the multiple-use zone (1.05, 1.01, 0.98) they relate to the GDP per capita; the added value of industry and total sales of consumer goods.

Table 5. Description of independent variables in each identified zone class.

Zone Classes	A	R_X^2	R_Y^2	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
Strict nature reserve	1	0.811	0.788	0.80	0.72	0.70	0.72	0.63	0.66	0.68	0.72	0.74	0.61	0.77	0.76
Protected zone	1	0.836	0.824	0.88	0.74	0.83	0.77	0.71	0.81	0.84	0.80	0.79	0.76	0.85	0.82
Extensive use zone	2	0.896	0.904	0.96	0.95	1.06	0.95	0.92	0.88	0.90	0.96	0.97	0.82	0.94	0.98
Intensive use zone	3	0.935	0.943	1.32	1.28	1.34	1.22	1.18	1.30	1.25	1.15	1.23	1.24	1.20	1.27
Recovery zone	4	0.920	0.936	1.03	0.96	1.05	0.90	0.88	0.94	1.06	1.08	1.12	1.10	0.92	1.01
Special use zone	3	0.901	0.887	1.06	1.05	1.02	1.08	1.11	0.92	0.94	1.02	1.04	1.01	1.08	1.07
Buffer zone	3	0.918	0.896	0.97	0.93	0.94	0.92	0.87	0.90	0.95	0.88	0.95	1.08	1.02	0.98
Multiple use zone	4	0.945	0.956	1.23	1.18	1.26	1.11	1.15	1.06	1.05	1.20	1.04	1.13	1.08	1.22
Common protection zone	2	0.882	0.894	0.94	0.95	0.92	0.90	0.93	1.05	1.01	0.98	0.85	0.87	0.90	0.87

A: the number of effective factors in each of the zone; ${R_X}^2$: the fitting degree of set X, which indicates independent variables; ${R_Y}^2$: the fitting degree of set Y, which indicates dependent variables.

4. Discussion

Rapid population growth and urban development have negatively impacted the environment and ecological resources of PAs. They have caused environmental pollution, habitat fragmentation, and a decrease in vegetation, and pose a threat to wildlife and key species in these habitats [44,45]. The contradiction between resource scarcity and community development has become a major problem in PAs located in urban areas [46,47]. Accordingly, the Jajrud Protected Area with the Sustainable Use of Natural Resources, located in the densely populated metropolis of Tehran, has been impacted by the major developments of this city and subsequent increases in visitation [9,26]. Human demand has exceeded the capacity of natural capital for this PA [48–50], leading to unsustainable levels of use in this area.

As the results demonstrate, high-density pasture decreased the most across our study years, while built-up increased the most. The Jajrud, as one of the oldest and largest PAs in the Tehran province, has seen rapid LULC changes due to continuous population growth, urbanization, industrialization, infrastructure development, expansion of transportation and road construction, the building of factories and mines, and excessive human utilization of natural resources. These findings are supported by other studies [9,26,51,52], which demonstrate that LULC change is one of the most critical problems facing PAs because it leads to changes in the structure and function of ecosystems and increases unsustainability in this area.

Likewise, EF has increased in 1989 compared to 2018, while ECC has decreased in this timeframe. Consequently, ED also in 1989 compared to 2018. This issue is also confirmed at the per-capita level, where ef and ed have increased from 1989 to 2018, while ec quantities have decreased in these years. Other studies have confirmed these findings [17,18,53], which have demonstrated human activities have exceeded their ECC because of an increasing EF, leading to a greater ED.

In addition, in this study, the results of the EF value analysis revealed that due to an increased price of biological resource products and human demand, the highest total EF^v is allocated to EF_B, followed by the highest value related to the EF_E. Likewise, per capita, the EF^v in this area also increased from 1989 to 2018. In contrast, ${EF_W}^v$ and ${EF_P}^v$ decreased, and so did the ratio of EF to the total ef^v.

The physical EPI compared to the value EPI has a higher rating. These results indicate that the imbalance between the supply and demand of natural resources is visible in this area. Moreover, these differences illustrate that human utilization of the environment and natural ecosystems have impacted ecological processes and regional sustainability.

The driving factors in natural capital utilization affecting the EPI were natural capital (for the per-capita ECC), resource consumption (for daily water consumption related), region size (for the level of built-up areas), economic development (for the added value of industry), and the ecological construction factor (for recovered areas). In addition, the results revealed that most driving factors in the strict nature reserve, protected zone, and common protection zone, were related to per-capita ECC and investment in biodiversity conservation projects and control development activities. In contrast, most driving factors in the extensive use zone, intensive use zone, recovery zone, special use zone, buffer zone, and multiple-use zone are allocated to factors related to various human activity developments (physical and economic), including daily energy and water consumption; resident population; level of built-up areas; per-capita GDP and finally, the added value of industry and total sales of consumer goods.

As we could demonstrate, the quantities of the EF and EC have greatly improved the accuracy of physical quantity calculations and added value to the EF model. These results have also been confirmed by Li et al. [17], which have shown that EF and EC, as relative indicators, enhance the accuracy of physical quantity calculations in an EF model.

5. Conclusions

This study examined the spatial and temporal changes in natural capital using an EF model for the Jajrud Protected Area with the Sustainable Use of Natural Resources, located in a semi-arid part of Iran. LULC changes directly relate to increasing EF and ED values while the ECC of natural resources and the environment decreased. Underestimating this serious issue will likely lead to further ecosystem degradation, shortage of resources, and ultimately increased unsustainability. Various illegal economic and physical uses of the Jajrud have changed LULC and caused extensive ED in this area. Industrialization, economic growth, and accelerated urbanization have caused spatial and temporal changes in natural capital. From a management perspective, our study identified that population growth, resource consumption, and economic development in the Jajrud Protected Area with the Sustainable Use of Natural Resources have seriously exceeded the maximum limits that resources can withstand. Therefore, a change in production and consumption patterns is necessary to navigate resource management towards sustainable levels. In this study, the calculation was performed based on the national average production, demonstrating the maximum real resource consumption situation at the local scale. Preventing the increase in LULC changes and protection of natural capital requires the creation of integrated management to develop sustainability and utilization of natural resources according to the ecological carrying capacity in the area. Identifying the driving factors for natural capital utilization for land zones that differ in their level of sensitivity, management goals, type of use, and human activity development constitutes one step towards managing these factors to improve land use conditions. In the future, one may consider calculating ecosystem service yield and biocapacity economic values and examining ecological security based on ecosystem service and EF.

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Abbreviations

The following abbreviations are used in this manuscript:

GDP	Gross Domestic Product
EF_B	Bio-ecological footprint
BRA	Biological resources account
COD	Chemical oxygen demand
ECC	Ecological Carrying Capacity
ED	Ecological Deficit
EF_E	Energy ecological footprint
EF	Ecological Footprint
EPI	Ecological Pressure Index
EF_W	Freshwater ecological footprint
LULC	Land use/land cover
NDVI	Normalized Difference Vegetation Index
OA	Overall accuracy
EF_P	Pollution ecological footprint
PA	Protected Area
RF	Random Forest
SDG	Sustainable Development Goal
USGS	United States Geological Survey

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