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Analysis of environmental sustainability using ecological footprint and bio-carrying capacity

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Original Research

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Abstract:

To achieve sustainable development, it is crucial to conserve natural lands and implement sustainable land-use strategies. Environmental sustainability can be measured using indicators like Ecological Carrying Capacity (ECC) and Biological Capacity (BC). In this study, the ecological sustainability and potential trends of land degradation of Khorasan Razavi in Northeastern Iran were assessed using both Ecological Footprint (EF) and biological capacity. EF was calculated based on a combination of carbon footprint, agriculture, horticulture, aquaculture, and protein production and BC was determined according to land-use patterns. These indicators were analyzed at both regional and county levels to assess overall sustainability. The study area exhibited an EF of 31 Million (M) global hectares (gha) and a BC of 12.7 M gha, revealing an ecological deficit and unbalanced land development. To mitigate this, an area approximately 2.4 times larger than the current one would be required. In some parts of the region, the EF was found to be 21.1 M gha-substantially surpassing the biological capacity of 1.2 M gha, further indicating unsustainable land use. Over time, the over-exploitation and degradation of natural lands have contributed to the widening gap between EF and BC. This ecological imbalance can be addressed by reducing consumption, improving production efficiency, adopting advanced eco-friendly technologies, and expanding green areas to boost carbon sequestration. In addition, effective land-use regulations are necessary to achieve long-term sustainable development goals.

Keywords: Ecological capacity; Human activities; Land degradation; Sustainable development; Khorasan Razavi province

Introduction

Population growth and its associated social and environmental impacts represent one of the foremost global challenges of the current era (IPCC., 2018; Wolff et al., 2021). This phenomenon is intricately connected to industrial development, the depletion of natural resources, soil degradation, biodiversity loss, escalating soil pollution, climate change, and widespread, often irreversible desertification—all of which pose significant threats to global development and human survival (Golia et al., 2021; Memarian and Akbari, 2021; Liu and Ni, 2023; Kashtabeh et al., 2023). The current trajectory of land degradation and desertification presents great risks to food security and environmental stability, affecting the well-being of at least 3.2 billion people worldwide. It is estimated that global food production could decrease by 12% within the next 25 years (UNCCD, 2020). Additionally, by 2030, global population growth and the rising demand for energy, food, and water are expected to place significant pressure on natural lands and ecosystems, with projected increases in demand of 50%, 45%, and 30%, respectively (IPCC., 2021). According to the FAO (Food and Agriculture Organization) (2015), over two billion ha of formerly productive land have been degraded, and more than 70% of natural ecosystems have been altered. Projections indicate that by 2050, global ecosystem degradation

may reach 90%.
To meet sustainable development goals, it is crucial to preserve both the quantity and quality of natural lands and to manage natural resource exploitation effectively (Hossin et al., 2024; Akbari and Alizadeh Noughani, 2024). Sustainability indicators must be integrated across local, regional, and national levels aligned with environmental laws and regulations (Ghita et al., 2018; Nabati et al., 2020; Sato et al., 2024). In this regard, ecological carrying capacity (ECC) is a vital endogenous indicator of regional sustainable development potential. It reflects the upper limits of socio-economic development within a region (He and Xie, 2019; Zhang et al., 2022). As such, ECC could play a key role in achieving sustainable development (Zhang et al., 2021). ECC represents the maximum population which a region can support without compromising its natural balance. Exceeding this limit results in nature imposing pressures-manifesting as destructive events like floods, droughts, famines, landslides, and land subsidence-as a response to unchecked human growth and activities (Taiwo and Feyisara, 2017; Akbari et al., 2019). Therefore, ECC allows for a quantitative assessment of environmental sustainability (Galli et al., 2020) and is considered as the threshold for human-induced environmental pressure. One of the most widely used methods for assessing ECC involves environmental indicators such as the ecological footprint (EF) and biocapacity (BC) (Swiader et al., 2018).
EF quantifies the amount of arable land and water required to produce the resources which a population consumes, support its development, and assimilate its waste (Dai et al., 2023). BC, on the other hand, measures the natural biological productivity of a region, reflecting its capacity for ecosystem services and regeneration such as carbon dioxide sequestration (Ozbas et al., 2019). The difference between EF and BC serves as an indicator of ecological conditions, as reflected by ECC. When EF exceeds BC, it signals an ecological deficit; conversely, when BC surpasses EF, it indicates a biological surplus, meaning that natural biological production exceeds resource demand (Galli et al., 2014).
Many researchers have utilized these two indicators to assess the environmental sustainability of various regions. For instance, Galli et al. (2020) calculated EF and BC for Portuguese cities to evaluate environmental conditions and resource management, concluding that EF is a valuable tool for assessing regional sustainability and managing resources in line with sustainable development criteria. Similarly, Li et al. (2021) evaluated ECC and EF for a Chinese city, finding that from 1995 to 2018, per capita EF increased by 2.83 times, while ECC decreased by 34.74%, leading to a 15.76-fold increase in the ecological deficit. Comparable studies have been conducted in Iran (Wang, 2022; Xie et al., 2022; Dai et al., 2023; Pourebrahim et al., 2023), the United States (Kirikkaleli et al., 2023), and on a global scale (Moros-Ochoa et al., 2022). A review of these studies reveals that carrying capacity has been widely applied in environmental planning and management, playing a critical role in regional environmental resource management (Feng et al., 2018).
Approximately 17% of Iran's desert area is located in the eastern province of Khorasan Razavi, where nearly 5.5 million ha (48%) are characterized by an arid climate. All 33 counties in this province are affected by climatic and atmospheric conditions typical of deserts, with 22 facing significant wind erosion. Studies in Khorasan Razavi Province have identified recurrent droughts, excessive groundwater extraction, overexploitation of woodlands and pastures, inappropriate cropping patterns, neglect of crop rotation, and vulnerability to erosion as the primary factors contributing to desertification over the past 30 years. Reports indicate that six out of the province's 37 plains are in a critical state concerning land subsidence. For example, the Mashhad Plain is experiencing subsidence at a rate of $15-17$ cm annually. If current trends in drought and excessive groundwater extraction continue, land subsidence will persist, leading to irreversible aquifer degradation (Office, 2021b). Additionally, hazards such as drought, erosion, and landslides continue to pose significant risks to Khorasan Razavi province (Office, 2021a).
The primary goal of this research is to assess the ecological carrying capacity in Northeastern Iran, with a particular focus on the escalating degradation and the alarming spread of desertification in the region. These risks, primarily driven by excessive and unsustainable exploitation of natural resources, have resulted in widespread environmental degradation and the loss of valuable ecosystems in the province. This study seeks to evaluate the region's carrying capacity by calculating biocapacity (BC) and ecological footprint (EF), which are essential indicators of the balance between resource supply and human demand. By auditing the supply and demand of natural resources, the research aims to provide a clear picture of the current state of resource consumption and environmental pressure in the area. In light of the ongoing damage to the region's ecosystems, this assessment is crucial for identifying the extent of overuse and proposing actionable solutions to mitigate further environmental degradation and improve sustainability in the region. The findings of this study will help inform policies and management strategies that could slow or reverse the desertification process, ensuring a more sustainable future for Northeastern Iran.

Materials and methods

Study area

The study was conducted in Khorasan Razavi province, located in northeastern Iran, which is predominantly characterized by arid and semi-arid climates. The province experiences an average annual precipitation of approximately 208 mm and an average temperature of around 16 °C, based on 20-year averages. The proximity of the Karakum Desert in Turkmenistan to the north has increased the region's vulnerability to degradation and desertification (Office, 2021a). Khorasan Razavi province contains nearly one million ha of forested land, accounting for about 8.4% of the province's area and one-twelfth of Iran's forested land, alongside 5.5 million ha of desert, which constitutes one-sixth of the country's desert areas, making the province particularly susceptible to desertification. The annual per capita rate of desertification in the province is about half a hectare, compared to the global average of roughly two-tenths of a hectare (Memarian and Akbari, 2021; Akbari et al., 2022). Approximately 1.6 million ha or 11.8% of the province's total area are directly impacted by wind erosion (Rashki et al., 2021). These areas are characterized by solonetz soils, which contain soluble salts at a depth of 100 cm and are highly susceptible to salinization due to agricultural practices and irrigation (USDA-SCS., 1993; USDA., 2014). Contributing factors to desertification in the study area include the increasing number of wells, land-use changes from pastures and woodlands to agricultural and residential areas, and soil salinization (Akbari et al., 2022; Nabati et al., 2023). Given the current natural hazards in the region resulting from the misuse of natural resources, this research was conducted to assess sustainability in the province. The geographical location of the study area is illustrated in figure 1.

Research method

This study aims to calculate ecological carrying capacity (ECC) for Khorasan Razavi province to assess sustainable development and analyze the environmental hazards resulting from the over-exploitation of natural resources using ecological footprint (EF) and biological capacity (BC). Both EF and BC were evaluated at the county level to assess sustainability across the province. EF assessment focused on carbon footprint and included separate evaluations for agriculture, horticulture, protein production, and aquaculture. These results were then summarized and integrated to assess the overall EF of the province. The flowchart of the research process is presented in figure 2.

Total EF in a region refers to the EF of all activities associated with the production of goods and the assimilation of waste. This index is calculated according to equation (1) (Galli et al., 2020).

$$\mathrm{EF} = \sum_{i=1}^{n} \frac{P_i}{Y_{W.i}} \times \mathrm{EQF}_i \tag{1}$$

where:
EF is Ecological footprint
P is the amount of each primary product i harvested in a region;
$Y_{W,i}$ is the average annual global yield for the production of product i; and
EQF_i is the equivalency factor for the land-use that produces product i.
BC is an ecological indicator capturing the capacity of ecosystems to meet human demands. BC is calculated according to equation (2) (Galli et al., 2020).

$$\mathrm{BC} = \sum_{i} A_{N.i}.YF_{N.i}.\mathrm{EQF}_i \tag{2}$$

where:
BC is biological capacity
$A_{N,i}$ is the biologically productive land available in a region for producing product i;
$YF_{N,i}$ is the productivity coefficient specific to the area (related to the land that produces the product i), and

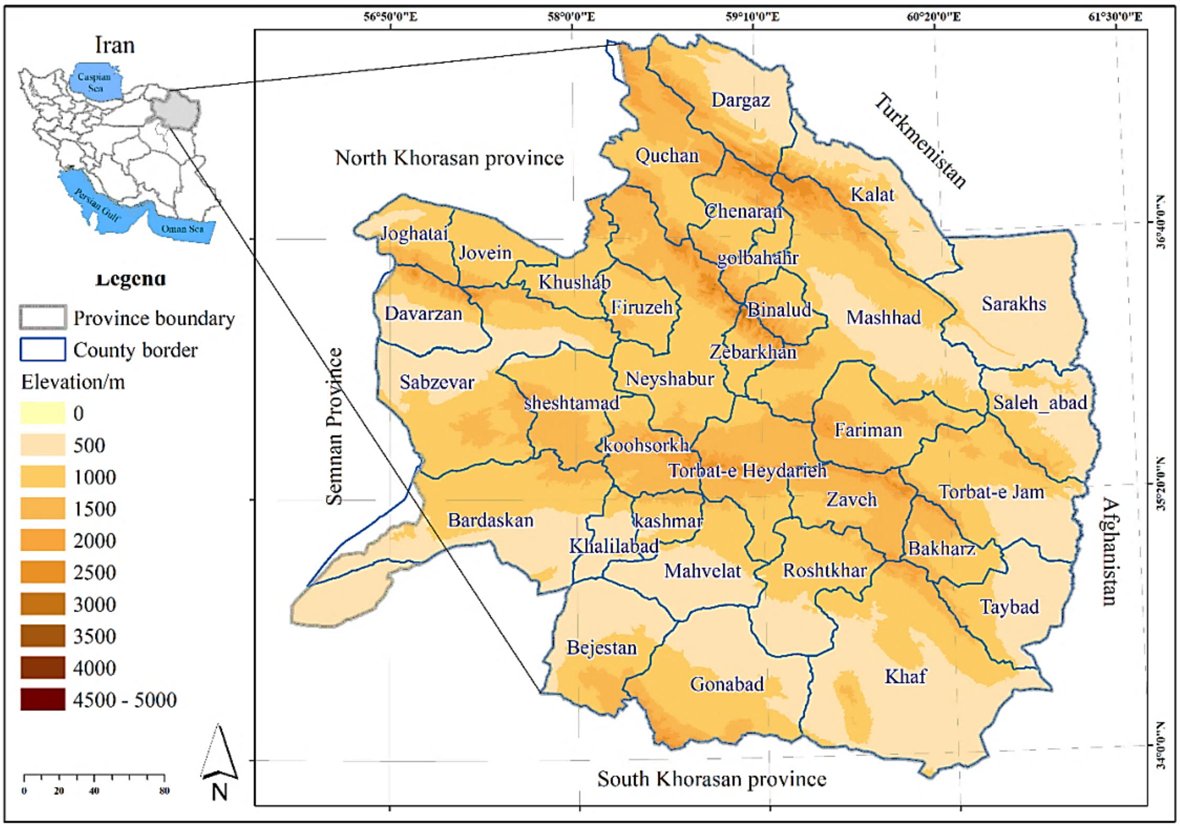

Figure 1. The map of elevation in the Counties of Khorasan Razavi Province in Iran.

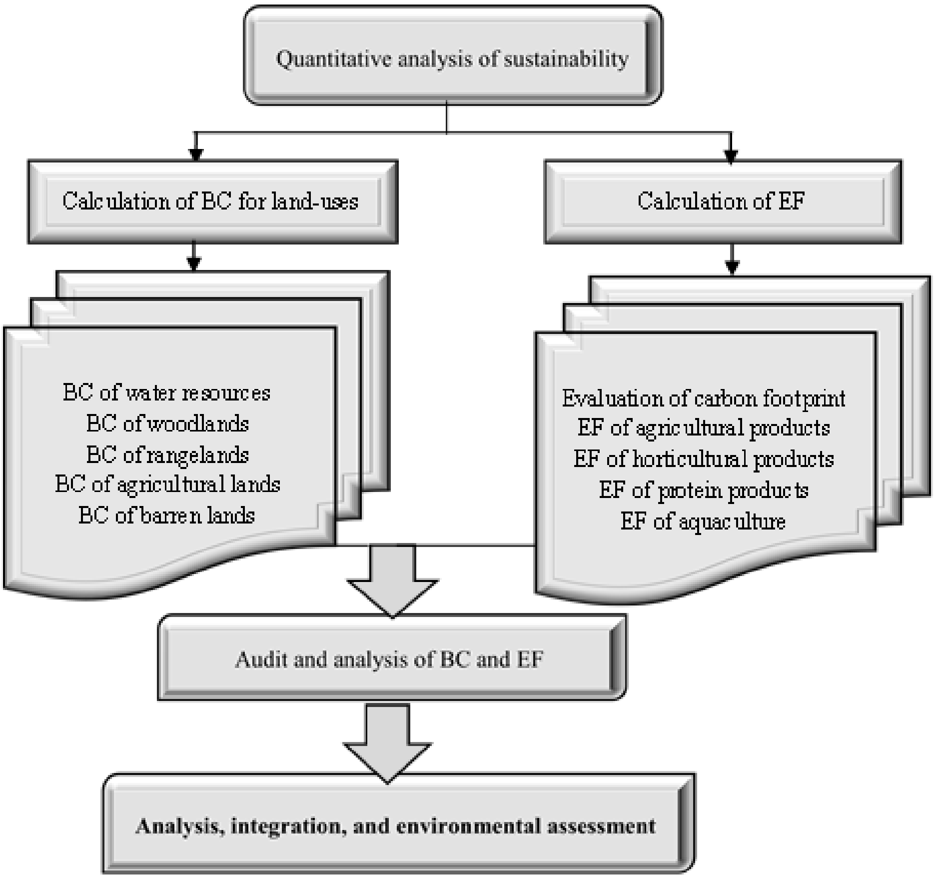

Figure 2. Flowchart of the research process, including Ecological footprint (EF) and biological capacity (BC) calculation, as well as audit and analysis.

EQF_i is the equivalency factor for the land-use that produces product *i* (Galli et al., 2014).

Both EF and BC are expressed in a standard global unit called the "global hectares" (gha), which represents one hectare of biologically productive land or sea with the average global biological productivity for a given year (Galli et al., 2020).

EF and BC are interrelated: EF represents the biologically productive area required by a population for sustainable resource provisioning and waste assimilation, while BC represents the available biologically productive land. These concepts are analogous to supply and demand in economics. When EF exceeds BC, the region experiences a deficit in renewable resources. Conversely, when EF is less than BC, it indicates a biological reserve (Galli et al., 2020; Dai et al., 2023). Therefore, the relationship between EF and BC provides a clear illustration of resource use and sustainability within a region.

EF assessment for the study area was conducted based on carbon footprint, and separate evaluation of EF for agriculture, horticulture, protein production, and aquaculture at the county level.

Calculation of EF for carbon footprint

To evaluate the carbon footprint, first, the amount of carbon dioxide emitted through the consumption of energy carriers (i.e., electricity and natural gas) was calculated. The gas and electricity consumption figures for the year 2020 were extracted from statistical yearbooks for rural and urban areas, and the corresponding CO_2 emissions were calculated. To calculate average carbon sequestration, total carbon sequestration in the study area was divided by the area of land that can potentially sequester carbon. Finally, the carbon footprint for each county was calculated as follows:

YN = 35,938221 tone carbon sequestration ÷ 11,080662 ha = 3.24

EQF for carbon = 1.28

EFC for CO_2 emission $= YN \times 1.28$

EFC is the emissions factor at consumption for CO_2 emission, and YN is the average provincial yield for production or waste assimilation (in tons per hectare), Average carbon sequestration in counties was calculated based on average carbon sequestration for each major land use according to available sources and considering the characteristics and conditions of each land use. The area of each land use in a county was multiplied by the corresponding carbon sequestration figure. Total carbon sequestration for a county was equal to the sum of values for all present land uses.

Calculation of EF for agriculture and horticulture

To calculate EF, the total agricultural production of the study area (4,782251 tons) in 2020 was divided by the area of agricultural lands in the province (620755 ha). A similar process was utilized for horticultural production. Table 1 shows the formulas and their calculations for each product

Table 1. Calculation of EF for agriculture, horticulture, and protein production in the study area.

Products	Formulas and the calculations for each product in this area
Agriculture	P = 4782251 tons (total agricultural production) $Y_n = P \div 620755$ ha (area of agricultural lands) = 7.70 tons /ha EQF = 2.5 EFA Agriculture = $P \div Y_n \times$ EQF
Horticulture	P = 1107650 tons (total horticultural production) $Y_n = P \div 372439$ ha (area of horticultural lands) = 2.97 tons /ha EQF = 2.5 EFA Agriculture = $P \div Y_n \times$ EQF
Protein production	YN = 3151452 tons ÷ 6603934.58 ha = 2.21 tons/ha EQF = 0.46 EF of protein production = $P \div Y_n \times$ EQF

(Note: To calculate EF, the total yield of protein production in the province was divided by the area of rangelands.)

in the study area.

Audit and analysis

The total EF for each county was calculated based on carbon footprint and the EF values for agriculture, horticulture, protein production, and aquaculture. Subsequently, EF was compared with BC for each county and the results were analyzed.

Results and discussions

Carbon Footprint

The central counties in the province had the largest carbon footprints, especially Mashhad (the provincial capital) and Neyshabur, with emissions ranging from approximately 2 to 21 million tons (Table 2), indicating high energy consumption. The main reasons for the high carbon ecological

Table 2. Carbon dioxide emissions and carbon sequestration in tons for each county in Khorasan Razavi province.

County	Electricity Consumption (MWh)	Natural Gas Consumption (10^3 m^3)	CO_2 Emission (tons)	Carbon Sequestration (tons)
Bajestan	68208	22,636	6312	34560
Bakhzar	48335	51,745	13042	21554
Bardaskan	290774	74,204	21560	59501
Chenaran	446602	30662	79350	3411
Dargaz	86057	5648	14665	3608
Davarzan	91609	2659	7564	1091
Fariman	478094	25289	66862	46058
Firuzeh	122575	11180	28414	38631
Golbahar	257227	-	3318	20075
Gonabad	214082	13267	34603	45216
Joqatai	166404	13267	33988	3138
Jovein	200545	34421	85197	3667
Kalat	17761	2467	6150	22380
Kashmar	314992	24119	61949	12587
Khaf	264728	24817	62977	765
Khalilabad	144226	4846	13491	1821
Khoushab	109940	3357	9476	4026
Koohsorkh	15903	-	205	19578
Mahvelat	226693	5663	16516	47963
Mashhad	13852440	80484	211032	15164
Neyshabur	738401	93188	233177	101918
Quchan	291000	24931	63590	58896
Roshtkhar	222654	5388	15803	5939
Sabzevar	575646	36772	95679	73316
Salehabad	42966	20,705	5523	31539
Sarakhs	182870	17083	43359	47948
Taybad	402699	682,498	168994	58167
Torbat Heydarieh	497031	40201	102895	6073
Torbat Jam	581865	168,430	47929	52506
Torqabe Shandiz	248142	103,690	28086	10511
Zave	155128	20174	50419	30848
Zebarkhan	313042	-	4038	16071

footprint in these two counties are the high population density and the consequent increase in resource use.
Carbon sequestration was notably higher in the central, southern, and western counties, as indicated in Table 2 and figure 3. The counties with the greatest carbon sequestration were Mashhad (1,516,391 tons), Neyshabur (1,019,188 tons), Khaf (764,993 tons), and Sabzevar (733,164 tons). The elevated levels of carbon sequestration in Mashhad and Khaf are attributed to the extensive woodlands, croplands, and orchards in these areas. Mashhad County alone contains approximately 23,800 ha of forests and 400,000 ha of croplands and orchards, while Neyshabur has around 23,000 ha of forests and 294,000 ha of croplands and orchards. On the other hand, Torghabeh-Shandiz recorded the lowest carbon sequestration at 105,113 tons, primarily due to its limited forested area (about 2,000 ha) and small extent of croplands and orchards (around 20,000 ha). Increasing carbon sequestration capacity in this county and other similar areas could be achieved through the restoration and expansion of forests and rangelands. Therefore, additional research is needed to identify suitable lands for development and to pinpoint areas that are most suitable for green space development. In most counties, carbon sequestration was less than emissions (Table 2). The most significant disparity was seen in Golbahar and Salehabad, where carbon sequestration was approximately six times higher than emissions. In contrast, Mashhad County exhibits a notable imbalance, with CO_2 emissions nearly 14 times greater than its carbon sequestration capacity (figure 3). Counties located in the western and eastern regions of the province, particularly Taybad (over 1.6 million tons), Sabzevar (over 900,000 tons), and Torbat Heydarieh (over 1 M tons) had notably high emissions. On the other hand, Kalat recorded the lowest emissions, with around 43,000 tons (figure 3).

Calculation of carbon footprint

Mashhad had the largest carbon footprint (around 9.2 M gha), followed by Neyshabur (around 1 M gha). The smallest carbon footprints were observed in Koohsorkh and Golbahar, with approximately 899 and 14,500 gha, respectively (Table 3 and figure 4).

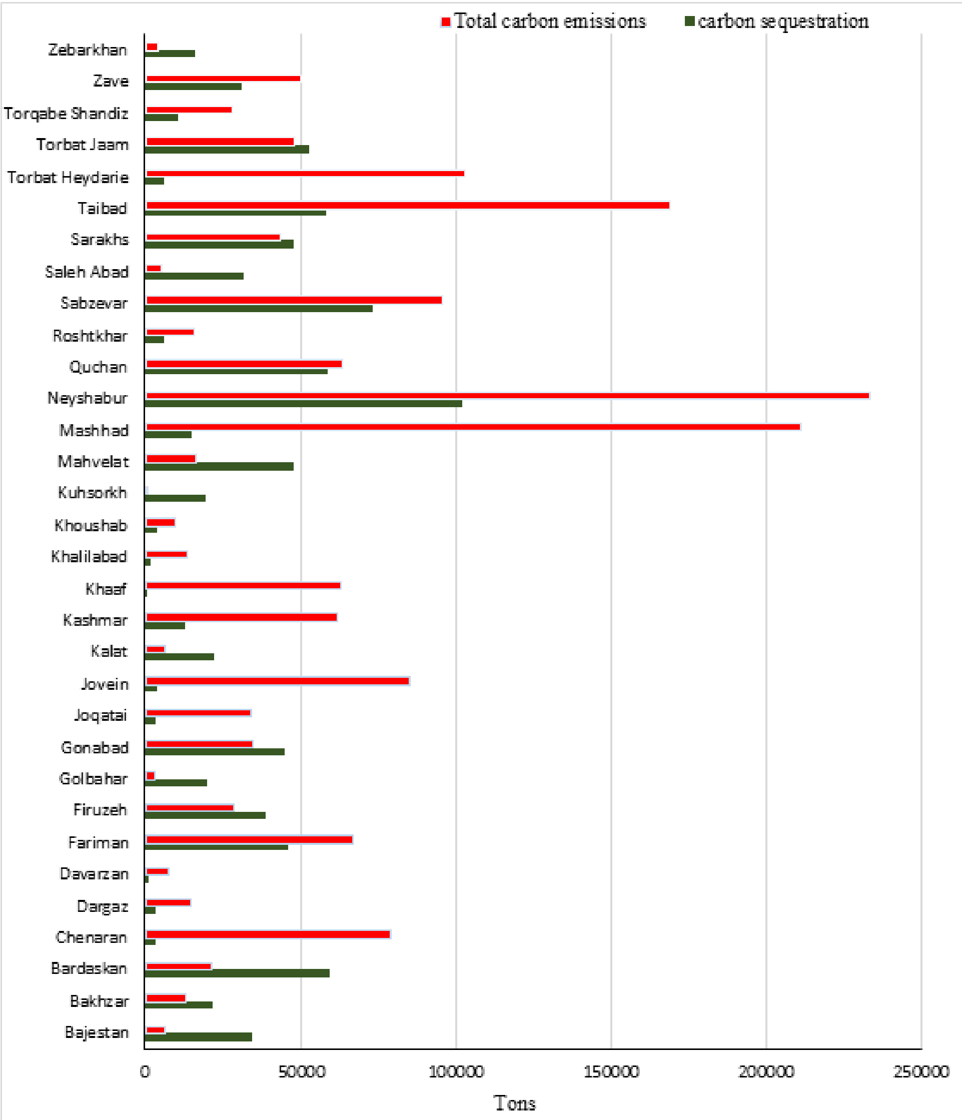

Figure 3. CO_2 emission and carbon sequestration in Counties of Khorasan Razavi province, Iran.

Table 3. Total carbon emissions and carbon footprint in Counties of Khorasan Razavi province, Iran.

County	Total carbon Emissions (Tons)	Carbon Footprint (gha)	County	Total Carbon Emissions (Tons)	Carbon Footprint (gha)
Bajestan	63125	27671	Khoushab	94765	41541
Bakhzar	130423	57171	Koohsorkh	2051	899
Bardaskan	215600	94509	Mahvelat	165167	72402
Chenaran	793506	347838	Mashhad	21103186	9250711
Dargaz	146657	64288	Neyshabur	2331777	1022149
Davarzan	75649	33161	Quchan	635901	278751
Fariman	668621	293094	Roshtkhar	158037	69276
Firuzeh	284139	124554	Sabzevar	956797	419418
Golbahar	33182	14545	Saleh Abad	55235	24212
Gonabad	346030	151684	Sarakhs	433598	190070
Joqatai	339884	148990	Taybad	1689944	740797
Jovein	851978	373470	Torbat Heydarieh	1028959	451050
Kalat	61501	26959	Torbat Jam	479293	210101
Kashmar	619499	271561	Torqabe Shandiz	280867	123119
Khaf	629774	276065	Zave	504195	221017
Khalilabad	134915	59140	Zebarkhan	40382	17701

EF of agriculture, horticulture, and protein production

Mashhad had the largest agricultural EF, while Neyshabur had the largest EF associated with protein production. Chenaran and Torbat Jam is also high in terms of agricultural EF. The smallest agricultural and protein production of EF was found in Salehabad (Table 4 and figure 5).

Relationship between total production and EF values

The EF for a class of products is primarily influenced by total production. Figure 6 illustrates the relationship between total production and EF. A comparative analysis of this figure reveals that Mashhad had the highest agricultural output in 2020, with 734,215 tons, leading to the largest agricultural EF. Neyshabur, which produced the highest amount of protein products (533,440 tons), also had the largest footprint associated with protein production. On the other end of the spectrum, Salehabad with 46,330 tons of agricultural production and 1,264 tons of protein production had the smallest EF related to both agricultural and protein outputs. The data also showed significant variations in yield across different product categories, which directly impacts EF. The provincial average yield has been given for protein production, horticulture, aquaculture, and agriculture as 2.21, 2.97, 2.99 and 7.7 (ton/ha), respectively. The relatively low yield in agricultural production highlights the need for strategies to enhance productivity.

Calculation of biological capacity (BC)

The total and per capita BC for each county and the entire province derived from the sum of BC for land uses is presented in Table 5. The distribution of total and per capita BC across the study area is presented in figure 7.

Audit and analysis of relationship between EF and BC

Total EF and BC for the province were 31 M global hectares (gha) and 12.7 M gha, respectively (Table 6). Mashhad had the largest EF, and Firuzeh had the largest per capita EF (figure 8). Also, the largest difference was observed in Mashhad, followed by Neyshabur, and Sabzevar.

The results indicate that Khorasan Razavi province would require an area roughly 2.4 times its size to offset the ecological footprint of its population. This suggests that the region's ecological carrying capacity (ECC) was being ex-

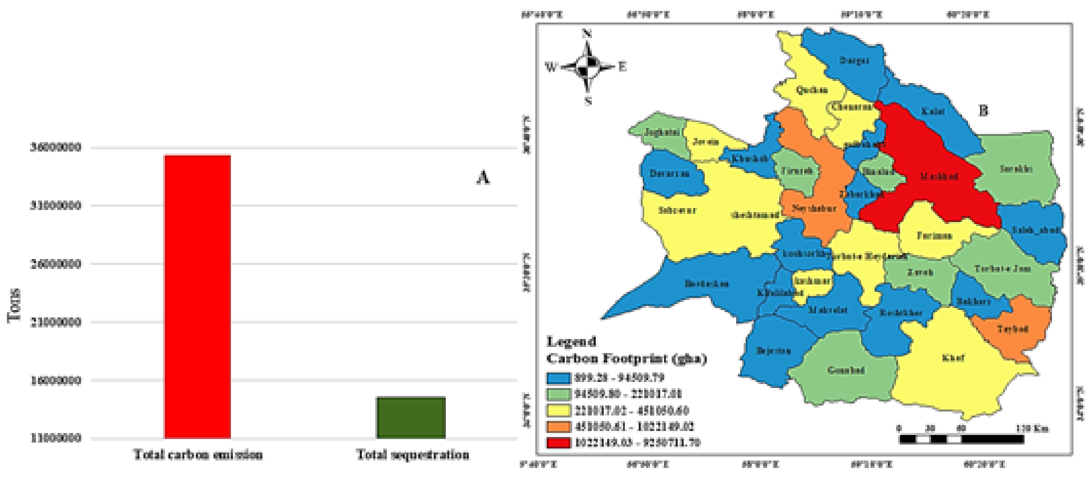

Figure 4. Total carbon emission and sequestration in Khorasan Razavi province (A), and carbon footprint map by county (B).

Table 4. Agricultural, horticultural, and protein production outputs and the corresponding ecological footprint (EF) in Counties of Khorasan Razavi province, Iran.

County	Agriculture (Tons)	EF of Agriculture	Horticulture (Tons)	EF of Horticulture	Aquatic Products (Tons)	EF of Aquatic Products	Protein Production (Tons)	EF of Protein Production
Bakhzar	16755	5439	1905	1603	110	13.61	40977	8542
Bajestan	8906	2891	15771	13275	3	0.37	12335	2567
Bardaskan	32048	10405	59415	50012	335	41.45	17937	3774
Taybad	342202	111104	8641	7273	136	16.83	20487	4281
Torbat Jam	508964	165248	15554	13092	49	6.06	83127	17308
Torbat Heydarieh	335133	108809	19303	16248	322	39.85	63922	13344
Joqatai	262082	85091	13240	11144	186	23.02	27982	5847
Jovein	327819	106434	16547	13928	92	11.38	27475	5730
Chenaran	405616	131693	141586	119180	970	120.03	114223	23894
Khalilabad	7054	2290	146565	123371	26	3.22	13085	2726
Khaf	73434	23842	6340	5336	33	4.08	25961	5407
Khoshab	47789	15515	18093	15229	79	9.78	9830	2055
Davarzan	109823	35656	11212	9437	1032	127.71	22339	4777
Dargaz	73284	23793	16954	14271	204	25.24	29358	6135
Roshtkhar	94143	30565	8035	6763	21	2.6	16491	3435
Zave	38659	12551	3178	2675	112	13.86	23334	4870
Sabzevar	157510	51139	25765	21687	2808	347.48	76387	16247
Sarakhs	163183	52981	1015	854.4	181	22.40	20965	4386
Salehabad	45479	14765	850	715.5	220	27.22	6077	1292
Torqabe Shandiz	2748	892.2	49195	41409	924	114.34	39023	8236
Fariman	230200	74740	29244	24616	162	20.05	40655	8482
Firuzeh	114984	37332	7606	6402	142	17.57	27982	5841
Quchan	179599	58311	117780	99141	408	50.49	76068	15883
Kashmar	53632	17412	87629	73761	105	12.99	38956	8121
Kalat	32404	10520	11227	9450	565	69.92	14370	3060
Gonabad	32094	10420	21966	18489	51	6.31	95389	19861
Mashhad	620183	201358	114032	95986	704	87.12	239799	50000
Mahvelat	15652	5081	56439	47507	28	3.46	13902	2897
Neyshabur	450872	146387	82563	69497	1399	173.12	337289	70378
Total	4782251	1552679	1107650	932365	11407	1411.56	1575725	329390

ceeded, leading to land degradation and underscoring the urgent need for remedial actions. Potential measures to address this deficit include expanding green spaces and enhancing sustainable land management practices (e.g. Kashmar, Torbat Heydarieh, and Torbat Jam, which had small areas of forests and cultivated land) based on land capacity, developing eco-friendly technologies (such as solar panels, irrigation monitoring, wind power, recycling, and carbon capture), and replacing fossil fuels with renewables. Given the region's favorable climate, there is significant potential for harnessing solar and wind energy, making renewable energy an attractive and viable solution. Consequently, further research is essential to identify the most suitable areas for development.

Our findings with those reported by Li et al. (2021) in Ürümqi, China, showed that the city needs nearly four times

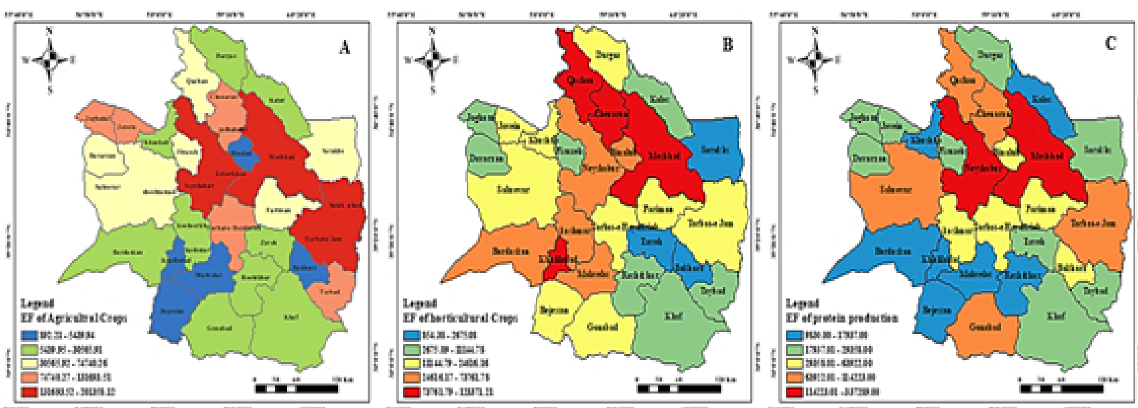

Figure 5. Ecological footprint (EF) maps for agriculture (A), horticulture (B), and protein production (C) Counties of Khorasan Razavi province, Iran.

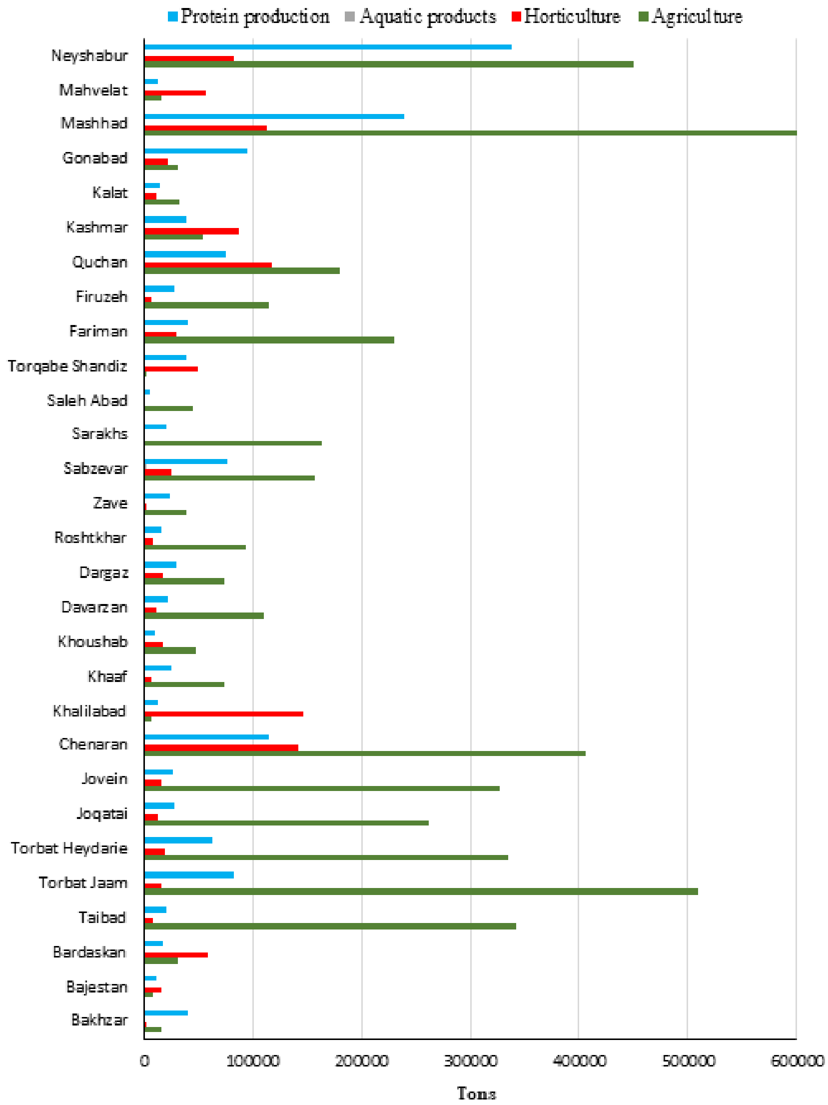

Figure 6. Production in agriculture, horticulture, aquaculture, and protein production in Counties of Khorasan Razavi province, Iran.

its current land area to sustainably meet its residents' resource consumption needs. The study identified ecosystem degradation (e.g., deforestation, water scarcity, agricultural expansion, rapid urbanization, population growth, and unsustainable economic development) as the primary causes of reduced BC and ecological deficit. The researchers suggest solutions such as controlling population growth, improving resource use efficiency, utilizing renewable energies, optimizing industrial structures, and developing sustainable and balanced urbanization, which align with the findings of the current research. Xie et al. (2022) studied the sustainability of Shanghai, China, using both EF and BC, found an ecological deficit in the area. They suggested that implementing strategies such as the development of better regulations, along with the enhancement of port production and operational facilities, could contribute to the reduction of EF.

Dai et al. (2023) analyzed sustainability over 10 years (2010 – 2019) in a region in China through an EF and BC audit. The results indicated a 15-fold increase in BC and a 30-fold increase in ecological deficit, indicating the need for improving productivity and efficiency. They also recommended the adoption of renewable energies and limiting fossil fuels to reduce the carbon footprint. Pourebrahim et al. (2023) employed a similar approach to quantitatively analyze land sustainability in Alborz Province, Iran and found an ecological deficit in the area. They identified issues such as unbalanced land development, degradation of protected areas, and land-use change favoring industrial and residential development as the causes of environmental instability and ecological deficit in the region. Zhang et al. (2023) also used BC and EF to assess sustainability, and stated that total BC was central to sustainability analysis. Qiu et al. (2021) emphasized the importance of conservation and establishing a dynamic balance between human needs and the natural environment's carrying capacity as goals of the United Nations' sustainable development plan. Kirikkaleli et al. (2023) acknowledged the importance of reducing EF and stated the need to use eco-friendly technologies to resolve conflicts between economic development and environmental considerations. They also emphasized the replacement of fossil fuels with renewable energies and the promotion of eco-friendly technologies by governments.

Table 5. Total and per capita biological capacity (BC) in Counties of Khorasan Razavi province, Iran.

County	Total BC (ha)	Per Capita BC (gha per person)	County	Total BC (ha)	per Capita BC (gha per person)
Bajestan	241213	21.24	Koohsorkh	296084	34.17
Bakhzar	220583	21.76	Mahvelat	386720	15.61
Bardaskan	470736	13.58	Mashhad	1245954	0.35
Chenaran	251397	3.59	Neyshabur	819210	2.53
Dargaz	426996	11.37	Quchan	525965	4.97
Davarzan	225888	63.24	Roshtkhar	433887	51.35
Fariman	479914	10.44	Sabzevar	593495	1.87
Firuzeh	258037	35.83	Salehabad	380536	36.18
Golbahar	142485	2.97	Sarakhs	556432	11.97
Gonabad	419122	10.15	Sheshtamad	448320	110.81
Joqatai	216678	18.93	Taybad	512253	8.08
Jovein	263579	15.88	Torbat Heydarieh	480153	3.12
Kalat	252547	39.56	Torbat Jam	688730	5.62
Kashmar	114780	1.00	Torqabe Shandiz	105625	6.38
Khaf	742120	17.92	Zave	373867	35.02
Khalilabad	135478	8.44	Zebarkhan	225888	32.28
Khoushab	280377	36.31			

Carrying capacity defines a region's ability to endure excessive pressures without environmental degradation. To prevent escalating environmental challenges, standards and guidelines must focus on the effective implementation of regional policies by developing land-use plans and managing ecosystem loads within this carrying capacity. Land-use guidelines serve as essential tools in regional planning, ensuring that development aligns with the principles of sustainable growth. These controls are designed to enhance environmental quality and improve the well-being of local communities (Taiwo and Feyisara, 2017).

Conclusion

This study quantitatively analyzed environmental sustainability using EF and BC in Khorasan Razavi province, Iran. The results showed that the province was in ecological deficit, with a total EF of 31 M global hectares (gha) and a total BC of 12.7 M gha. To sustainably meet the needs of its population, the province needs an area about 2.4 times larger than its size. A detailed analysis of the relationship between EF and BC provided key insights into the state of natural resource use and the environmental impact of communities across different counties.

The BC estimation results showed that counties in the central, eastern, and western regions of the province, particularly Mashhad, Neyshabur, Sabzevar, and Khaf had the highest levels of BC. However, counties in the central part of the province, especially Mashhad, had the lowest BC per capita (0.35) gha per person due to their large populations. Other counties with low per capita BC (e.g., Kashmar, Torbat Heydarieh, and Torbat Jam) had small areas of forests and cultivated land to supply the basic needs of their populations. Consequently, it is essential to strategize for the expansion of green spaces in alignment with the specific environmental conditions of these areas.

The study of total and per capita EF showed that central counties such as Mashhad and Neyshabur had the largest total EF, and Firuzeh has the largest per capita EF (39.45)

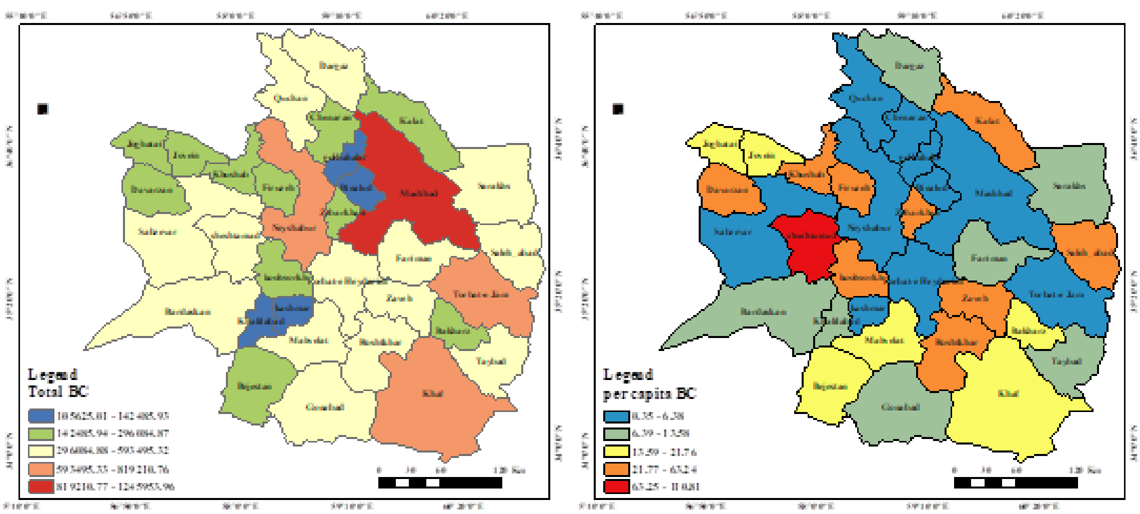

Figure 7. Total and per capita biological capacity (BC) in Counties of Khorasan Razavi province, Iran.

Table 6. Total and per capita ecological footprint (EF) in Counties of Khorasan Razavi province, Iran.

County	Total EF (ha)	Per Capita EF (gha per person)	County	Total EF (ha)	Per Capita EF (gha per person)
Chenaran	451,050	39.4	Koohsorkh	346,030	8.38
Dargaz	276,065	35.75	Mashhad	2,331,777	7.21
Davarzan	59,140	1.43	Quchan	635,901	6.01
Fariman	668,621	14.55	Roshtkhar	41,541	11.63
Firuzeh	284,139	39.45	Sabzevar	433,598	9.32
Golbahar	21,103,186	5.94	Salehabad	50,538	3.05
Gonabad	165,167	6.67	Sarakhs	55,235	5.25
Joqatai	740,797	6.05	Taybad	27,671	2.44
Jovein	210,101	1.36	Torbat Heydarieh	123,119	1.94
Kalat	61,501	7.1	Torbat Jam	94,509	2.73
Kashmar	619,499	5.4	Torqabe Shandiz	57,171	5.64
Khaf	373,470	5.34	Zave	69,276	6.49
Khalilabad	148,990	8.97	Zebarkhan	956,797	3.02
Khoshab	347,838	21.66			

gha per person. A significant portion of EF in Firuzeh was attributable to carbon emissions, as evidenced by the electricity and gas consumption statistics. Therefore, gradual lifestyle changes are needed to reduce EF. Mashhad, Neyshabur, and Sabzevar had the greatest ecological deficit. In contrast, BC exceeds EF in Bardascan, Khaf, Mahvelat, and Torbat Heydarieh, indicating greater potential for carbon sequestration. This contrast reveals the unsustainable distribution of population and activities across the province and improper land-use management. The main challenges in the region are land degradation and the loss of natural reserves due to over-exploitation, as reflected in the discrepancy between EF and BC.

Two sets of strategies can be beneficial for addressing this issue. The first set of strategies focuses on reducing EF by adjusting population size, lowering per capita consumption, and increasing resource and production efficiency. Efficiency can be improved through the use of advanced technologies and equipment in the industry, effective irrigation, and demand-driven agriculture. The second set of strategies involves increasing BC through expanding green areas to increase carbon sequestration.

While this study provides valuable insights into the environmental sustainability of Northeastern Iran, it has some limitations. The reliance on global coefficients for ecological footprint and biocapacity calculations may simplify complex regional ecological dynamics, potentially affecting the precision of the results. Additionally, the study's focus on current conditions without incorporating long-term ecological changes such as climate shifts, limits its foresight. Furthermore, while the county-level analysis is insightful, a more granular approach might uncover localized variations. Finally, the proposed solutions, though promising, could benefit from more detailed strategies for practical implementation.

We recommend identifying suitable locations for expanding green spaces within the province. Additionally, it highlights the urgent need for studies focused on developing eco-friendly technologies such as solar panels, irrigation monitoring, wind power, and recycling, to protect and restore natural resources in the region.

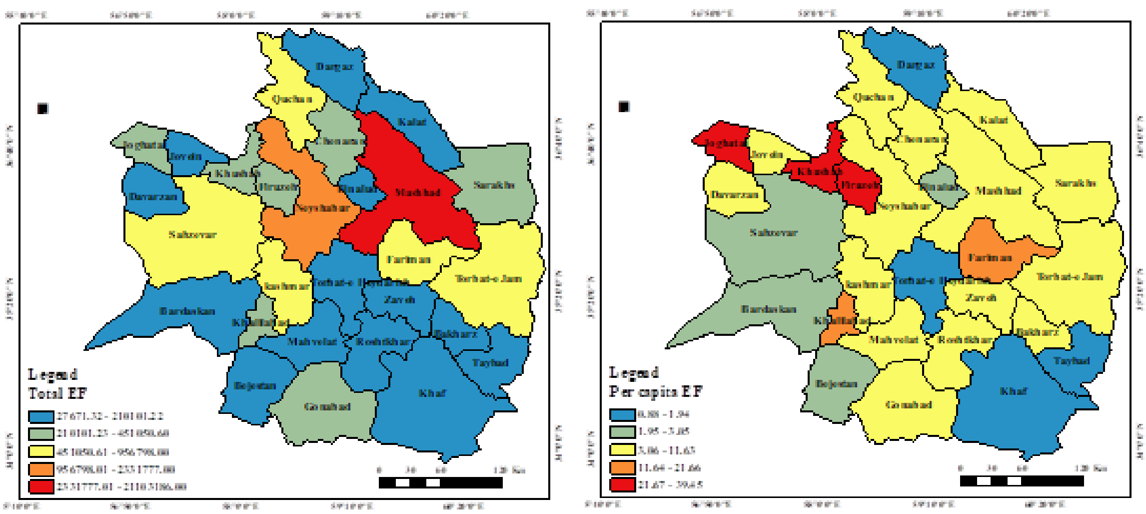

Figure 8. Total and per capita Ecological Footprint (EF) in Counties of Khorasan Razavi province, Iran.

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Authors Contributions

All authors have contributed equally to prepare the paper.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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