Heliyon 9 (2023) e15079

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A mathematical meta-model for assessing the self-sufficient water resources carrying capacity across different spatial scales in Iran

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ARTICLE INFO

Keywords:
Population
Carrying capacity
Ecological footprint
Meta-model
Spatial scale

ABSTRACT

Hydrological modeling, water accounting assessments, and land evaluations are well-known techniques to carry out water resources carrying capacity (WRCC) assessments at multiple spatial levels. Using the results of an existing process-based model for assessing WRCC from very fine to national spatial scales, we propose a mathematical meta-model, i.e., a set of easily applicable simplified equations to assess WRCC as a function of high-quality agricultural lands for optimistic to realistic scenarios. These equations are based on multi-scale spatial results. Scales include national scale (L0), watersheds (L1), sub-watersheds (L2), and water management hydrological units (L3). Applying the meta-model for different scales could support spatial planning and water management. This method can quantify the effects of individual and collective behavior on self-sufficient WRCC and the level of dependency on external food resources in each area. Carrying capacity can be seen as the inverse of the ecological footprint. Hence, using publicly available data on the ecological footprint in Iran, the results of the proposed method are validated and give an estimation of lower and upper bounds for all biocapacity of the lands. Moreover, the results confirm the law of diminishing returns in the economy for the carrying capacity assessment across spatial scales. The proposed meta-model could be considered a complex manifest of land, water, plants, and human interaction for food production, and it could be used as a powerful tool in spatial planning studies.

1. Introduction

Human carrying capacity (K) is the maximum potential number of inhabitants supported sustainably within a region considering human-environment interaction [1]. There are multiple methods to estimate K, at any scale, which are classified into six categories [2]. Most of them are based on limiting factors and Liebig's Law of the Minimum. Human carrying capacity is dependent on imports and exports of the area. The dependency can be highlighted by estimating self-sufficient carrying capacity assessment [3–5]. Multiple studies concluded that state-of-the-art modeling dictates seeing the system as a complex adaptive system (CAS) with intertwined elements as a Social-Ecological System (SES) [6–10]. After publishing the seminal work "Limits to Growth" by Meadows et al. [10],

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https://doi.org/10.1016/j.heliyon.2023.e15079
Received 3 December 2022; Received in revised form 19 March 2023; Accepted 27 March 2023

scholars have tried to model both ecological and social processes into coupled models to show these limits to Growth [10,11]. Multiple examples, like the Lund-Potsdam-Jena managed Land (LPJmL) model [1], are based on the plant's photosynthesis as the limiting factor. Other examples are the EARTH3 [12] and EARTH4 [13] models, which include not only ecological limits in the form of planetary boundaries but also consider socio-economical limits using the system dynamics (SD)-based sub-model [14,15].

K modeling is a comprehensive work with many disciplines involved, as previously explained by Graymore [16], Lane [5], and Goldin [8] in independent studies, and can be formulated as follows [17]:

$$K(t) = SES\left(K_{Biophysical}(t), K_{Social}(t)\right) \tag{1}$$

where $SES()$ is the representative of the SES system and $K(t)$ is its output. The $K_{Biophysical}(t)$ is a limit of the population that the resources of a region can support at a specific level of food production technology to satisfy human needs. The $K_{Social}(t)$ is the sustainable population number using a given social organization [1].

In Iran, a water-scarce country, water consumption in the agricultural sector remains about half as efficient as the global average [18]. Government policies regarding food self-sufficiency have been very harmful and are compounded by population growth and global warming. As such, there is increased pressure on water availability in Iran, and the depth of the problem only increases [19]. Self-sufficient water resources carrying capacity (WRCC) is a useful concept to deal with water-security issues for policy orientation and human adaptability. In this regard, Khorsandi et al. [17] developed a general tool for WRCC assessment to determine how many people can be self-sufficiently fed in Iran. However, their modeling effort was highly complex. Linking such a complex model with social or economic models for spatial planning is intensive and can impact the further use of WRCC models. Therefore, for additional holistic assessments, especially for large-scale planning, the WRCC models should be quantified with reliable mathematical models as described for carrying capacity by Cohen [2] and for all systems by Cohen and Stewart [20] using mathematical formulations. To our knowledge, there is no previous study to represent WRCC in mathematical formulations across spatial scales. This paper shows how complex WRCC models can be simplified across spatial scales for Iran. In other words, here, a set of easily applicable simplified equations to assess WRCC as a function of high-quality agricultural lands for optimistic to realistic scenarios is presented. This study aims to provide an approach to evaluate self-sufficient WRCC using a simple but robust mathematical model at different spatial scales in Iran. Later, we discuss the relevance of spatial self-sufficient WRCC to the ecological footprint concept, emphasizing its role in spatial planning and decision-making.

2. Materials and methods

The specific methodological steps of this study include (1) Estimation of theoretical WRCC [Method 1], (2) Estimation of realistic WRCC using human-appropriated net primary production (HANPP) [Method 2], (3) Deriving a relatively simple mathematical meta-model, and (4) Presenting a case study to demonstrate the use of the approach. Data were imported and analyzed in Google Earth Engine (GEE) environment. The GEE code used to estimate WRCC is freely available on github.com/mostafakhorsandi/WRCC.

2.1. Method 1: theoretical water resources' self-sufficient carrying capacity

The theoretical WRCC was calculated by Khorsandi et al. [17]. This optimistic estimate considers highly-efficient agriculture, which can produce unlimited food using limited water resources. When land productivity is no longer a limiting factor, the area of productive lands and available water for evapotranspiration would be limiting factors. In this case, available water and high-quality lands are allocated to agriculture, and a small piece of such land is allocated for human living infrastructure. The final equation used by Khorsandi et al. [17] is as follows:

$$K_{Method\ 1} = \lim_{h \to \infty} \frac{\frac{A \times h}{n}}{1 + \frac{B \times h}{n}} = \frac{A}{B} \tag{2}$$

where A is the productive area (m^2); h is harvest per unit of area (kg/m^2 or kcal/m^2); n is per capita food requirement (kcal/day/person); and B is per capita area in the form of infrastructure (house, roads, recreation) for each citizen. The representative area of suitable agricultural lands is needed at each spatial scale of analysis to implement the meta-model for the assessment of WRCC. This representative area is estimated by the method presented by Mesgaran et al. [21]. More information about the Method 1 can be found in Appendix 1 section in supplementary data.

2.2. Method 2: realistic water resources self-sufficient carrying capacity using HANPP

In this method, agriculture productivity is limited, and 25% of net primary productivity (NPP) (α) as HANPP [17] can be an upper limit proxy for optimum agricultural practice in Iran. Using this proxy, $K_{Method\ 2}$ could be estimated realistically using the following equation:

$$K_{Method\ 2} = \frac{\iint_A HANPP(x, y)\, dA}{n} \tag{3}$$

where HANPP is the human-appropriated amount of net primary production at the (x, y) coordinate over the A area (kcal/day/m^2).

More information about the method can be found in Appendix 1 section in supplementary data. A balance between available water and evapotranspiration was identified. Based on this balance, the productive area is calculated for both methods. This technique is explained in detail by Khorsandi et al. [17] and briefly explained in Appendix 2 in supplementary data.

2.3. Simple mathematical meta-model

The theoretical WRCC and the HANPP-based WRCC methods are empirical models that are able to assess WRCC at any spatial scale [17]. The central component is the maximum sustainably available water volume that balances the utilized, suitable lands for agriculture, as assessed by the land suitability methods, and the evapotranspiration from those lands, as calculated by crop models or evapotranspiration estimation methods. The first method considers infinite agriculture productivity, and the second uses more realistic agriculture production values. The output of these models can be used for land use, demography, and economic planning.

We derived mathematical equations as meta-models for regional soil, water, and population planning purposes for both methods described above. Hack-ten Broeke et al. [22] mentioned that the definition of a meta-model is "a simple model derived from another more complex model." In the case of the carrying capacity model, the meta-model must be able to estimate carrying capacity instead of directly using Method 1 or Method 2. So, the meta-model approximates the results from the original models.

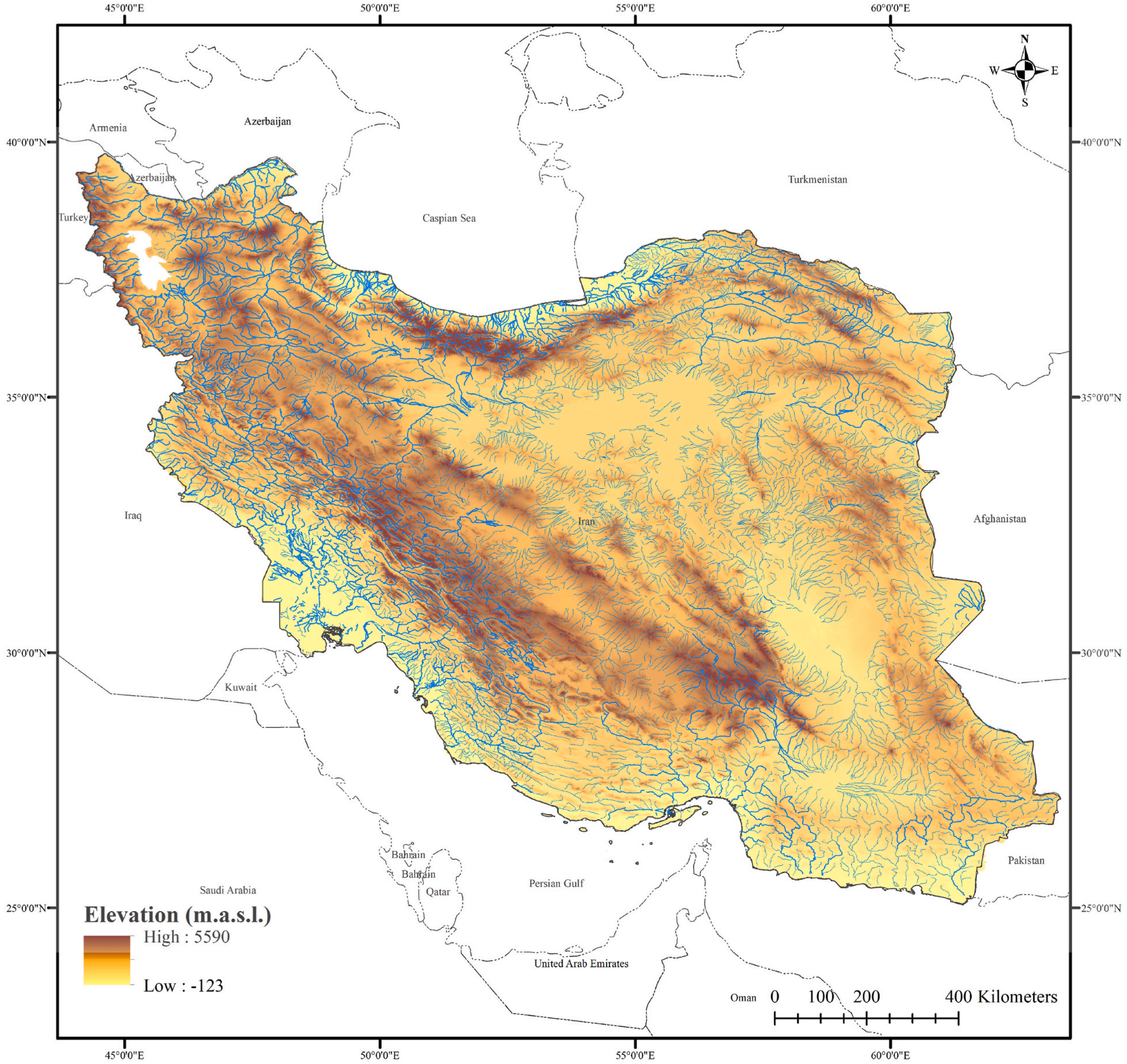

Fig. 1. Iran's geographical location, its neighboring countries, and the river network.

An advantage of developing a meta-model is that it requires less input data than the original model. Limited required input makes the meta-model an easily applicable tool without high computation costs. Using the representative area for each spatial scale as input and WRCC estimations at different scales from Methods 1 and 2, simple mathematical equations relate scale to WRCC. These meta-models generate the same model results with high accuracy. The meta-model we use for Iran's self-sufficient carrying capacity assessment is a basic logarithmic equation:

$$K = aLn(A) + b \tag{4}$$

where K is carrying capacity, A is a representative area at each spatial scale based on suitable lands for agriculture in the study area, a and b are constant parameters to be estimated. The equation selection was based on the apparent behavior in the results from the original methods at different spatial scales [Namely, national (L0), main watersheds (L1), main sub-watersheds (L2), and water management hydrological units (L3)].

A (representative area at each spatial scale) is the arithmetic mean of suitable lands for all study units at each scale. For L0, there is just one unit (the whole nation), while for L1 to L3, the number of study units is 6, 30, and 609, respectively. For calculation of A, the potential agricultural land area at each scale was first calculated with a balance between evapotranspiration and available water (Appendix 2 in the supplementary data).

2.4. Study area

Iran is the 18th largest country in the world, located in the Middle East, with 84 million inhabitants, and is the 19th most populous

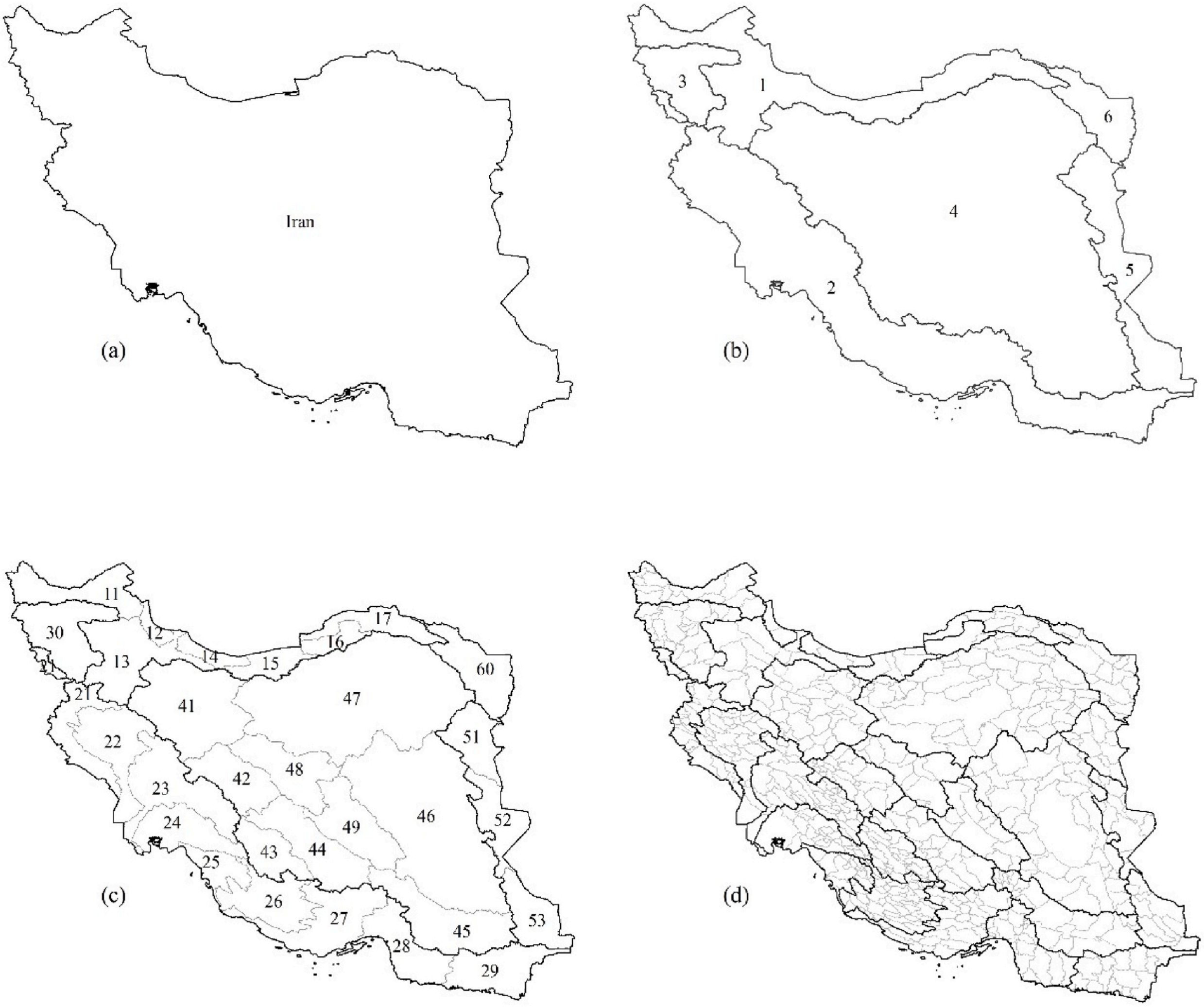

Fig. 2. Assessment units of this study for Iran: (a) national level or L0, (b) Main basins or L1, (c) main sub-basins or L2, and (d) study areas based on the Ministry of Energy in Iran or L3.

country in the world. Iran's area is 1,648,195 km^2 between 24° to 40°N and 44° to 64°E. This country has borders with Iraq to the west, Turkey to the northwest, Armenia, Azerbaijan, Turkmenistan, and the Caspian Sea (650 km) to the north, the Persian Gulf and Oman Sea (total of 1770 km) to the south, Afghanistan to the east and Pakistan to the southeast (Fig. 1).

The average annual precipitation is estimated at 250 mm, varying from 50 mm in parts of the central water basin to more than 1500 mm in some coastal areas near the Caspian Sea. 30% of precipitation occurs in the form of snow, and the rest falls as rainfall classifying Iran as arid and semi-arid [23]. About 117 BCM (billion cubic meters) of water is directly and potentially accessible by people through precipitation (internal renewable resources) each year. In addition to water resources gained through precipitation within the country's borders, about 13 BCM of surface flow enters the country across its borders. When this flow is combined with the surface flow with internal origins, the country's total surface water resources increase to about 130 BCM. Of this amount, about 13 BCM recharge alluvial aquifers. The agricultural sector has the most significant amount of water use, 83.5 BCM. The exploitation of water resources by the mining sector is about 1.1 BCM of total use. Withdrawal of water by the urban and rural water supply sectors is about 5.4 BCM of the country's water use [24].

As an arid/semi-arid country, Iran has limited surface water and groundwater resources and high geographical heterogeneity in supply and demand. Iran's territory has been divided into six main drainage basins (L1) and 30 main sub-basins (L2). These main sub-basins were then divided into 609 water study areas (L3) based on topography and the location and extent of aquifers (Fig. 2). These divisions are based on watershed units and without consideration of administrative divisions.

Iran currently faces a multitude of interconnected social, economic, and environmental challenges [25]. On a social level, the country is undergoing a transition from ideologically-driven autocracy towards a more democratic future driven by grassroots movements. Economically, Iran is grappling with six major challenges, including inflation, high unemployment rates, international sanctions, dependence on oil and gas exports, widespread corruption, and a weak infrastructure [25,26]. In terms of the environment, Iran is facing a daunting situation due to the loss of glaciers as a result of climate change [19,27], increased evapotranspiration due to rising air temperatures [27–29], excessive groundwater drawdown from agricultural use [19,30–33], and decreased precipitation over the past few decades [27,34,35]. Moreover, ambitious self-sufficiency policies have led to anthropogenic drought [17,32,33,36–38], further exacerbating the country's water crisis. These multiple and interconnected problems have created a complex and wicked problem that affects not only Iranian citizens but also has international implications, particularly for the stability of the Middle East region [25,26].

3. Results

The WRCC was calculated using both methods. In Method 1, all possible lands are used as long as there is water to evaporate from that area. Also, a 1500 m^2 per capita area was considered to satisfy each person's infrastructural needs. It means each person can fulfill all their non-edible needs in an area of 1500 m^2 (e.g., for housing, roads, infrastructure), and for their food, water is not a limiting resource. With high technologies like greenhouses, the problem of producing food is solved. The only limit is per capita lands used for making infrastructure in the city instead of agriculture from high-quality lands. These lands could be used for food production but are instead devoted to human settlement. Method 2 is based on Method 1, in which food production using photosynthesis is the main limit. The 25% NPP as HANPP was considered the limit for farming on all high-quality land in each study unit.

3.1. Method 1 results

The results for these theoretical *K* estimates are presented in Fig. 3a. The results are based on the representative area for each scale.

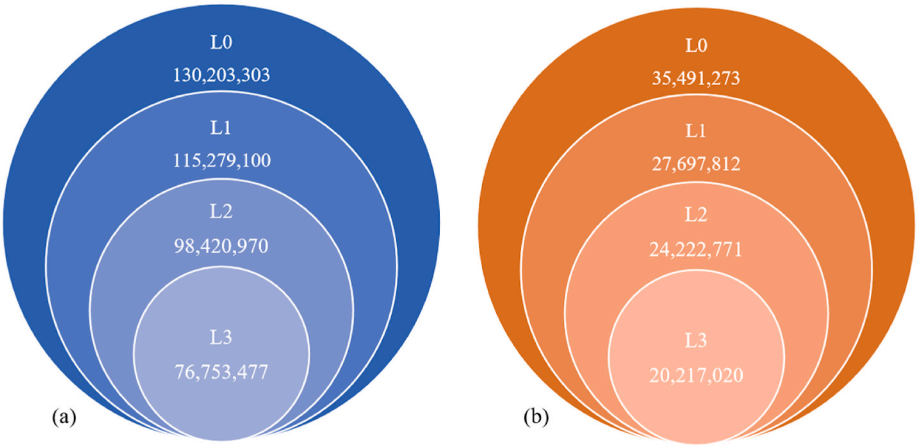

Fig. 3. The resulting values for national *K* across spatial scales using (a) Method 1, which is theoretical *K*, and (b) Method 2, which is HANPP-based *K*. For each method, the spatial scale is defined by the representative area.

These theoretical values varied from 76.75 to 130.2 million people at the national level based on the scale of analysis. For example, for L3, 189.05 km^2 is the average of 609 study areas, and 76.75 is the summation of K estimates in each study area at that scale. The same way was implemented for L0 to L2.

The non-uniform spatial distribution of estimated K is essential since water resources availability is highly uneven in Iran. This spatial distribution is shown in Fig. 4, where the relative share of the theoretical K in Method 1 for each study unit at the four spatial scales is presented.

Fig. 4 shows that different regions of Iran unevenly contribute to the K at the national level. By focusing on L0, the K value is 130.2 million people. However, it is assumed that the whole nation has access to the resources equally (Fig. 4a). This assumption means the food produced at the national level is available for inhabitants regardless of economic obstacles (e.g., the perfect synergy of humans and nature in the SES). By calculating K at more local scales, the national K value (sum of study areas) decreased to 115.3 for L1, 98.4 for L2, and 76.8 million persons for L3, respectively (Fig. 4b,c,d). By focusing on the local water resources (L3), it is visible that the main K contribution is close to the Alborz and Zagros mountains in Iran (Northern and Western regions), which have relatively higher precipitation compared to the central and eastern areas.

3.2. Method 2 results

Similar to Section 3.1 (Method 1 results), this section provides K values for L0 to L3 but uses HANPP values (Fig. 3b). The K value ranges from 20.22 (sum of 609 study areas at L3) to 35.5 million people (for the whole country or L0). The results of Method 1 (section 3.1) and Method 2 (section 3.2) are depicted in Fig. 3.

Fig. 5 shows that different regions of Iran unevenly contribute to producing HANPP and consequent K. By focusing on L0, the K value is 35.5 million people. However, it is assumed that the whole nation has access to the produced HANPP (Fig. 5a). This

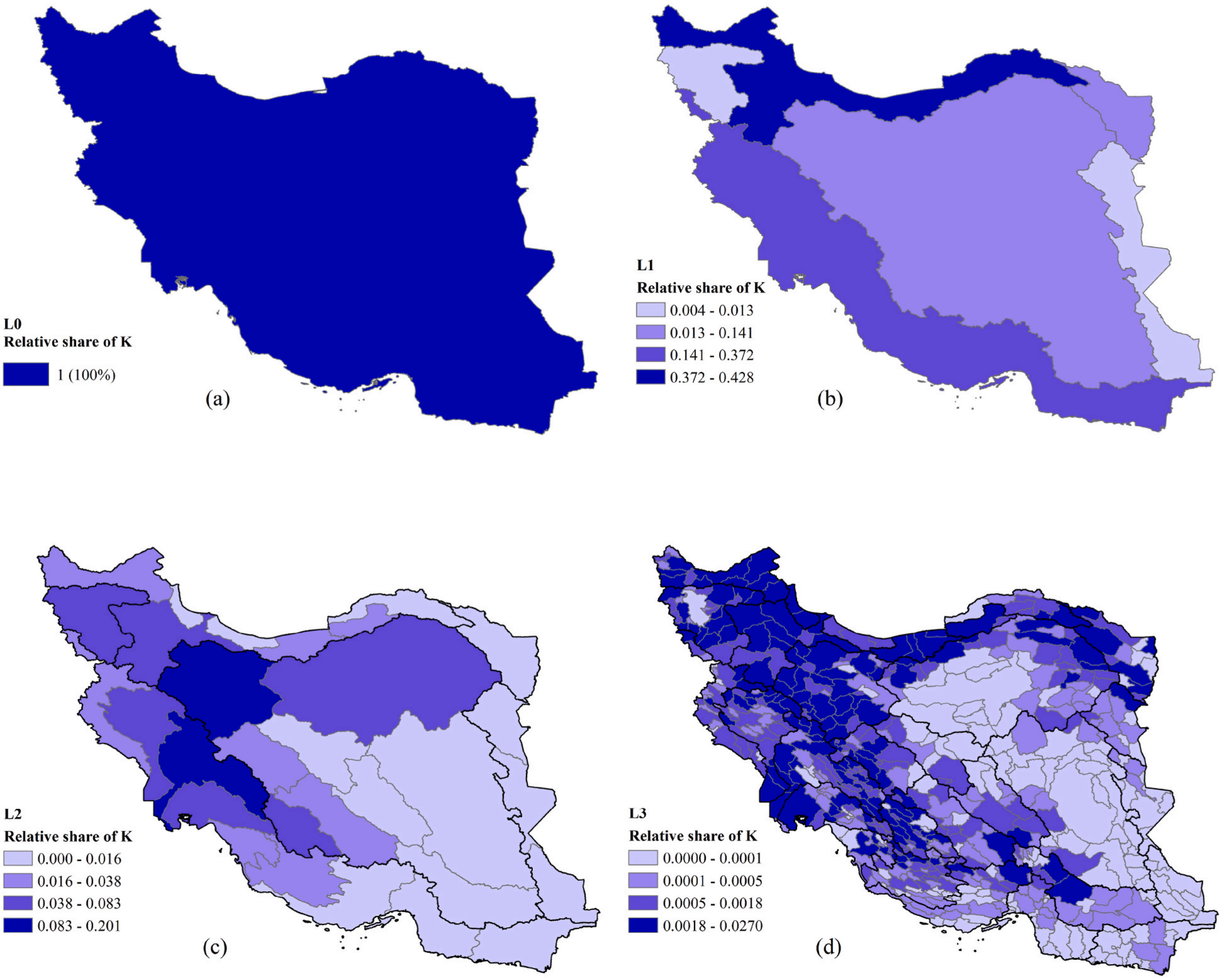

Fig. 4. The relative share of a national theoretical K (Method 1) for each study unit at four spatial scale assessments (a) one study unit at L0, (b) six study units at L1, (c) 30 study units at L2, and (d) 609 study units at L3.

assumption means a perfect economic market at work without considering social or economic obstacles (which means realistic harvest efficiency together with perfect human teamwork at the national level). By calculating K at the local scale, the national HANPP-based K values decreased to 27.7 for L1, 24.2 for L2, and 20.2 million people for L3, respectively (Fig. 5b,c,d). This figure shows the relative share of the K for each study area at the four spatial scales.

Method 2 considers three environmental limits for the carrying capacity: suitable agricultural lands, water availability, and HANPP. The pattern for the relative share of K for Method 2 is very similar to the pattern for Method 1. However, Fig. 5 shows by adding HANPP as an environmental limit, the relative share of the southwest of Iran, close to the Persian Gulf, decreases. This reduction can be related to water tension on the plants due to high potential evapotranspiration and low precipitation, which affect crop production.

3.3. Mathematical equations as the meta-model

Using the theoretical estimation of K at different scales in Method 1 and Method 2, the results show solid logarithmic relationships (Fig. 6).

The equation for this relationship for Method 1 is as follows:

$$K_{Meta-Model\ 1} = 8 \times 10^6\ Ln(A) + 3 \times 10^7 \quad (5)$$

Moreover, the resulting equation using a more realistic HANPP-based K in Model 2 is as follows:

$$K_{Meta-Model\ 2} = 2 \times 10^6\ Ln(A) + 8 \times 10^6 \quad (6)$$

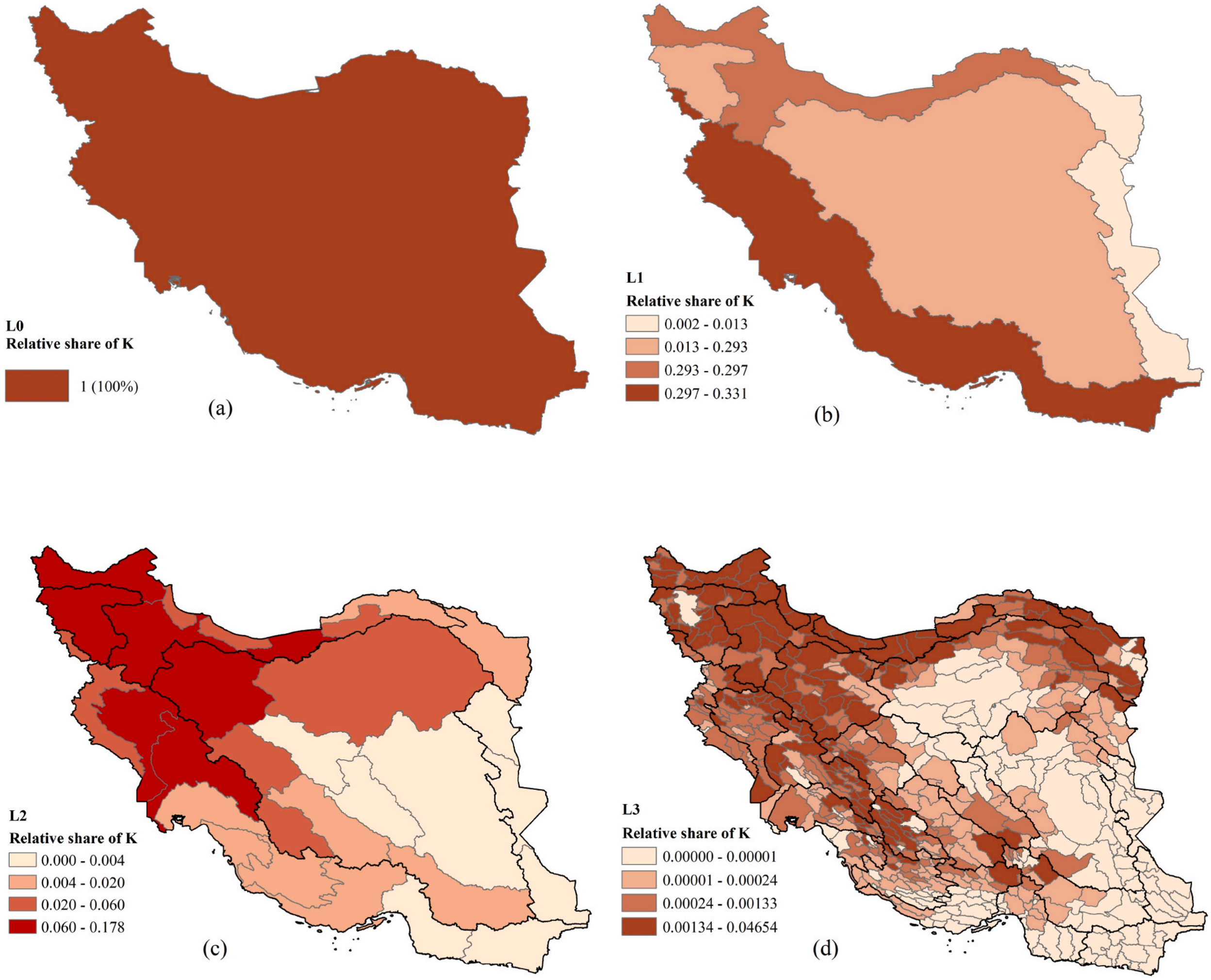

Fig. 5. The relative share of a national HANPP-based K (Method 2) for each study unit at four spatial scale assessments (a) one study unit at L0, (b) six study units at L1, (c) 30 study units at L2, and (d) 609 study units at L3.

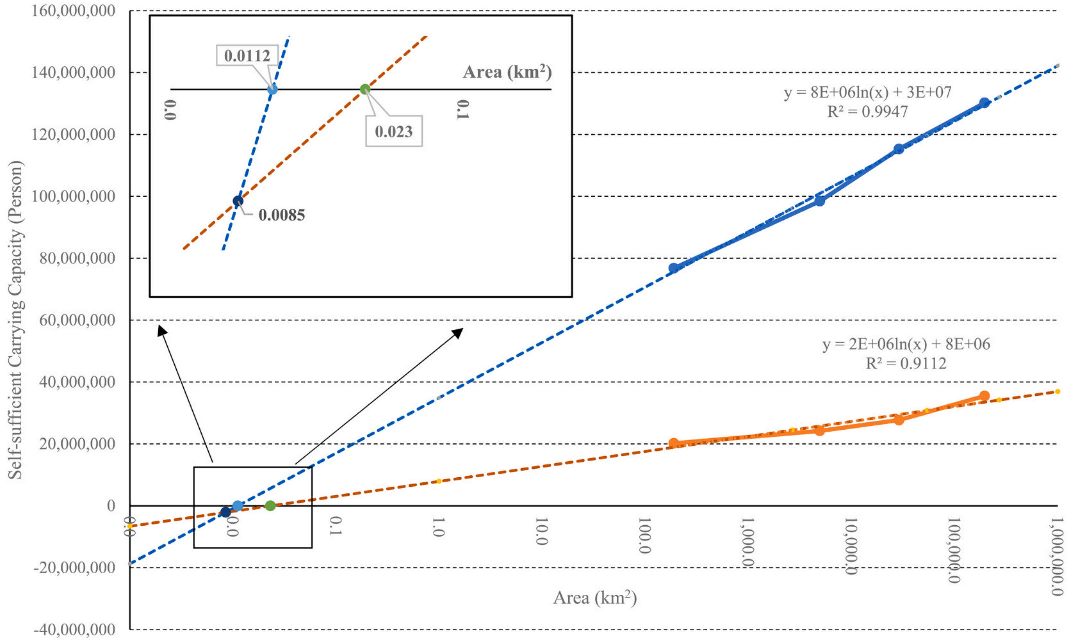

Fig. 6. *K* estimates using two methods at different spatial scales.

Two logarithmic lines are extended to intersect with each other and the x-axis (Fig. 6). Three critical points have resulted by interpolating these two lines in Fig. 6. The intersection of equation (5) and the x-axis shows the minimum high-quality land required to feed one person in Method 1, considering high-tech agriculture with suitable land as the limiting resource. This value equals 1.12 L ha

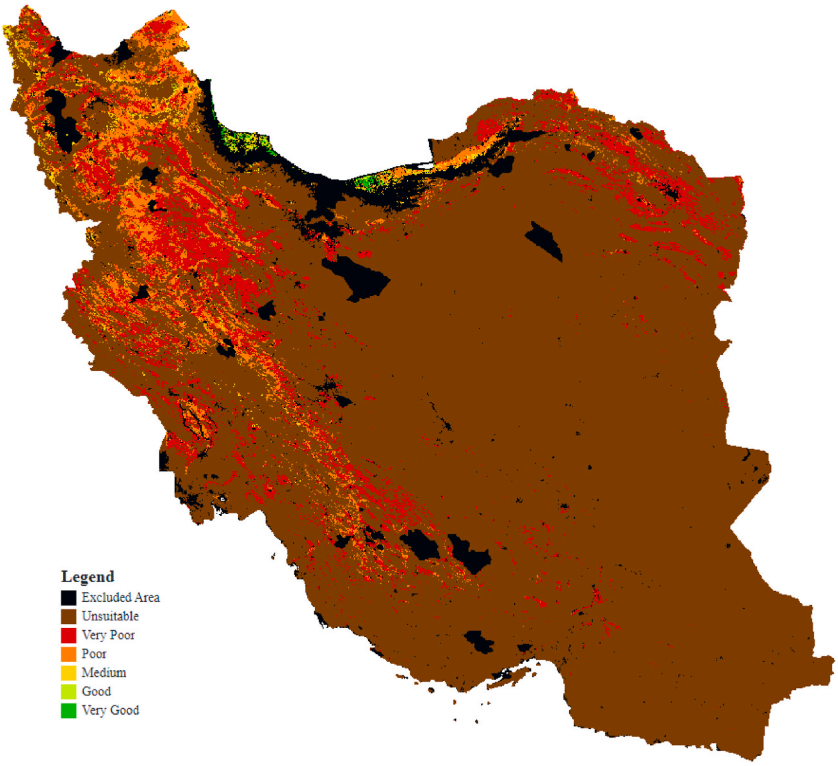

Fig. 7. Land suitability index map based on Mesgaran, Madani [21] using soil, climate, and topography conditions. This map was generated using the Google Earth Engine platform.

(Local hectare). The intersection of equation (6) and the x-axis results in 2.31 L ha for Method 2, which is based on water as the primary limiting resource and 25% of NPP as HANPP. The third point is the intersection of two lines (two methods). This point value is 0.85 ha and shows the representative area where the results of the two methods converge. The resulting negative value for K means land of this size is insufficient to feed one person, but the two method's results are the same if both analyses use this spatial resolution.

4. Discussion

4.1. Collapse of chaos

Food-crop production at the level of a single plant is a complex chain of reactions [22,39]. A patch of plants on the farm with intrinsic diversity and changes in external forces like weather and pests will add to this complexity [40,41]. However, at the end of the harvest season for each farm, those complexities will emerge simplified in a simple metric, "harvested yield." Again, after selling the harvest in the market, there is a chain of complex socio-economical interactions among farmers, suppliers, and the markets [41]. However, economists can simplify it into macro-scale regional indicators to work with it. We believe the same thing is happening here.

Similarly, a logarithmic relationship between K and A across different spatial scales has emerged. The logarithmic pattern was confirmed for both Methods 1 and 2. This emergent behavior was previously called "collapse of chaos" [20]. They called this phenomenon "simplicity" in the domain of "complexity theory" [42], which is confirmed when "complex causes can produce simple effects."

4.2. Why does logarithmic behavior emerge?

In this study, the carrying capacity relationship with the representative area (i.e., spatial scale) is logarithmic by going from the finer scale to the coarser spatial scale. One reason for this is the availability of suitable lands for agriculture. Going from small-scale farming to whole basin scale, the rate of adding suitable lands is less than the increase in scale. This phenomenon is a fact of Iran's geography that most lands are covered either by mountains or deserts, which are unsuitable for agriculture. The previously created map by Mesgaran et al. [21] showed how limited these lands are (Fig. 7).

For the first group of estimations of theoretical WRCC (Method 1), the main formula is equation (2). In this equation, though K and A has a linear relationship, the emergent relationship across spatial scales is logarithmic. This pattern will result in diminishing returns for increasing the area for agriculture. Since the current overall agricultural land in Iran is around 100,000 km^2, it could be seen from Fig. 7 that the increase in agricultural land would not return a significant increase in WRCC.

From an economic perspective, logarithmic behavior emerged because of the law of diminishing returns. The diminishing returns principle is valid in both micro and macroeconomics [43]. Assume the development of farmed lands for agriculture is an investment. As agricultural lands grow, the growth rate cannot continue considering any change in other agricultural inputs after a certain point. From agricultural development, the law of diminishing returns goes back to Malthus [44] when he wrote:

> "The improvement of the barren parts would be a work of time and labor; and it must be evident to those who have the slightest acquaintance with agricultural subjects that in proportion as cultivation extended, the additions that could yearly be made to the former average produce must be gradually and regularly diminishing."

Alternatively, instead of assessing K based on land area, one can imagine a scenario to calculate land area (ecological footprint) using the population number. The required land (to satisfy the needs) grows over-linearly with the population. This behavior typically shows exponential growth. A logarithmic behavior has emerged since K is the inverse of ecological footprint [5].

4.3. Example applications of mathematical meta-models for Iran

4.3.1. Land acquisition for agriculture

The results of the current mathematical interpretation of WRCC can be summarized in Fig. 6. This figure shows that considering HANPP/NPP = 0.25, the minimum land that can provide the food for one person in Iran, on average, should be as large as 2.31 ha in the local area (considering self-sufficiency assumption local hectare is the unit, while global hectare is the unit considering import and export in the international context). By eliminating the crop productivity limit (with advanced technology and land modifications), considering per-capita infrastructure equals 1500 m^2, 1.12 local hectares are still needed for each person. Moreover, these metrics can give decision-makers a minimum land area to allocate to every farming household. These two numbers have significant implications. The majority of farmers in Iran have farmlands of smaller sizes. It means they cannot live self-sufficiently, and cooperation should be one inseparable part of their lives for a possible synergy. At the same time, inheritance laws rooted in Islam split the land for later generations by giving more autonomy on land ownership. Besides, splitting lands decrease land usability for food production due to an increase in involved people, making it harder to cooperate among them. In this scenario, the tragedy of the commons is a possible destiny.

In Iran, in contrast to collectivistic societies, collective goals, and interests are less important than individual goals and interests [45]. Moreover, modern Iranian society has a high degree of individualism and a low degree of collectivism. Over the past two and half millennia, the country's history has been replete with autocratic, repressive, and corrupt regimes and frequent revolts [46]. These historical experiences may have helped reduce people's trust and respect for the collective system.

4.3.2. The cell size for remotely sensed analysis

Fig. 6 shows the 92 m cell size for the intersection point resulting from the two methods. This cell size is the least required spatial resolution of satellite images to converge two methods. For the current results, it can be inferred that any image with a resolution of 92 m or better would be enough for a large-scale carrying capacity assessment. This hypothesis should be tested using a third method of carrying capacity assessment using satellite images other than MODIS to confirm our results. Testing HANPP values based on Landsat or Sentinel images are recommended for this goal in future studies.

The other interpretation of this value (i.e., 8500 m^2 area) is that it can serve as a basis for SES studies with the minimum cell size as the primary variable to be determined [47,48], i.e., one that is adequate to investigate both social and ecological perspectives.

4.4. Comparing per capita results with ecological footprint databases

An ecological footprint is the inverse of the carrying capacity function [5]. Fig. 8 shows the per capita area based on this study compared to ecological footprint data (https://www.footprintnetwork.org/) confirmed by Refs. [49,50].

Fig. 8 shows that Iranian citizens' per capita ecological footprint increases while per capita biocapacity decreases. This study agreed with Khorsandi et al. [17], who showed that Iran exceeded its local self-sufficiency around 1957 and its national carrying capacity around 1975. The ecological footprint network data show that Iran exceeded the local and national carrying capacity before 1960 and possibly close to 1955, corroborating our results. Moreover, the ecological footprint network data shows that even if Iran had an extreme technological change to decrease per capita land requirement to less than 1.12 ha, the carrying capacity was exceeded around 1980. This conclusion confirms that Iran has not completed the technological change required for development, but this nation has faced local and national environmental bankruptcy since 1980. These three dates (1955, 1975, and 1980) are candidates that can lead us to tipping points in Iran's history from complex adaptive system (CAS) perspectives.

4.5. Limitations and future directions

The actual value of the HANPP/NPP ratio for Iran's agricultural lands is still unclear. The discrepancies among per capita land for each person using WRCC and per capita ecological footprint data show the need for such a realistic assessment for more precise analysis. It is anticipated that the objective food-based WRCC-based assessments based on national input-output economic assessments or agro-hydrological models like SWAT or SWAP will show smaller values than HANPP-based estimates since these models consider multiple constraints resulting in lower values for harvested yield. Besides, as a drawback of the HANPP technique for estimation of the carrying capacity, the measurement of food import/export on the short-term carrying capacity is ignored. Under these circumstances, new techniques like eHANPP can be utilized to estimate carrying capacity. Moreover, the accuracy of the input datasets is improving. Using data with higher spatial resolution can enhance the quality of the NPP product both spatially and temporally.

Many researchers, including [51], mentioned that sustainability should be considered a multi-objective state. Since sustainability is the core element of carrying capacity, a more comprehensive estimation of carrying capacity should not be limited to the population as the indicator. Other aspects, e.g., the size of the local economy, should also be included.

Our results show crucial times in Iran when some critical thresholds have passed. As discussed in the literature many times [52–55],

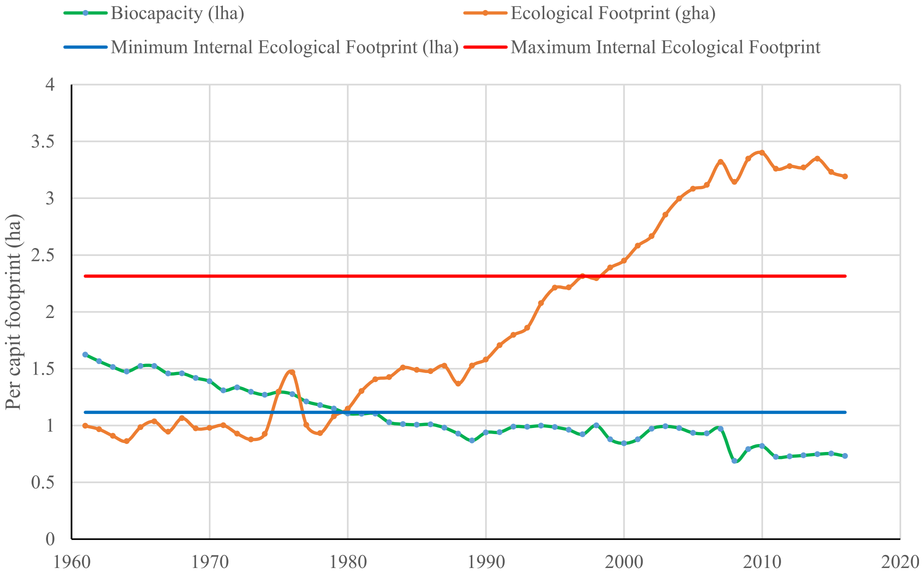

Fig. 8. Ecological footprint and biocapacity of Iran compared to resulting thresholds out of current research [lha = local hectare, gha = global hectare] (https://www.footprintnetwork.org/).

ecological footprint and carrying capacity can be used as early warning indicators of the systems. Surpassing them can lead to a tipping point for the SES. Further studies are needed to address the knowledge gaps related to Iran's tipping points.

By knowing only the area of suitable agricultural lands, it is possible to estimate the carrying capacity for each region (for example, a province or a county) using the meta-model derived for assessing self-sufficient water resources carrying capacity. It could be used to analyze internal migration patterns. However, due to the lack of data at the local level in Iran, such an assessment is impossible at this point. Therefore, collecting migration data and the relationship between WRCC and migration is recommended.

5. Conclusion

Any spatial population planning needs mathematical formulation that considers environmental limits and relates the spatial scale to the population carrying capacity. These mathematical formulations are essential for combining the economic aspects of planning with the ecological aspects. Mathematical meta-models of the WRCC relate the spatial scale to the carrying capacity for water-scarce regions, which is the primary constraint for the population's limits to growth. We formulated self-sufficient WRCC mathematically for spatial scales using suitable agricultural lands considering scale-dependent water availabilities. By using mathematical meta-models for theoretical and HANPP-based K values, the relationship between biocapacity data from the ecological footprint database and WRCC was found. The implication of our proposed meta-models was shown for spatial analysis, including spatial distribution of WRCC over the country.

Moreover, our models offer an analytical tool for spatial planning for human habitat suitability and internal migration analysis. This evaluation can show the regions and the number of people facing the danger of famine or malnutrition, or excess spatial pressure on natural resources because of overpopulation. The meta-models provide the minimum pieces of land to satisfy each person's nutritional needs as thresholds under optimist and realist scenarios. These per capita thresholds give the required minimum resolution of satellite imagery for future WRCC assessments and related SES analysis. The MODIS-based NPP product is suitable for estimating WRCC under the self-sufficiency assumption; however, the use of more up-to-date satellite data is recommended. This study can help the policymaking and population planning in arid-semi and arid areas of the world. Nonetheless, the need for more economic and social studies for WRCC is acknowledged. Also, the major knowledge gap is now on food import-export assessments for more precise WRCC estimations. New methods like eHANPP can be used for the carrying capacity assessment under these scenarios.

Supplementary data

Supplementary data for this article can be found in the "Supplementary data" file.

Declaration of competing interest

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. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Acknowledgments

This work is dedicated to our dear Mentor, Ali Rezagholi, whom we lost recently; peace be upon him. The authors would like to thank the anonymous reviewers for their insightful and constructive comments that will help us improve the quality of our study. The authors are grateful to Professor André St-Hilaire, and Professor Saeid Homayouni at Institut national de la recherche scientifique (INRS), Quebec, Canada, for their valuable comments on the earlier versions of this manuscript. To all dear Iranian farmers who lost their farmlands due to inadequate large-scale land planning.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e15079.

References

[1] S. Franck, W. von Bloh, C. Müller, A. Bondeau, B. Sakschewski, Harvesting the sun: new estimations of the maximum population of planet Earth, Ecol. Model. 222 (12) (2011) 2019–2026.
[2] J.E. Cohen, Population growth and earth's human carrying capacity, Science 269 (5222) (1995) 341.
[3] M. Lane, Exploring short-term and long-term time frames in Australian population carrying capacity assessment, Popul. Environ. 38 (3) (2017) 309–324.
[4] M. Lane, L. Dawes, P. Grace, The essential parameters of a resource-based carrying capacity assessment model: an Australian case study, Ecol. Model. 272 (0) (2014) 220–231.
[5] M. Lane, The Development of a Carrying Capacity Assessment Model for the Australian Socio-Environmental Context, PhD, 2014.
[6] G. Branderhorst, Update to Limits to Growth: Comparing the World3 Model with Empirical Data, 2020.
[7] D. Collste, J. Randers, U. Goluke, P.E. Stoknes, S. Cornell, J. Rockström, The Empirical Bases for the Earth3 Model: Technical Notes on the Sustainable Development Goals and Planetary Boundaries, 2018.

[8] I. Goldin, Is the Planet Full? Oxford University Press, USA, 2014.

[9] G. Herrington, Update to limits to growth: comparing the World3 model with empirical data, J. Ind. Ecol. 25 (3) (2021) 614–626.

[10] D.H. Meadows, E.I. Goldsmith, P. Meadows, The Limits to Growth, Earth Island Limited London, 1972.

[11] D.H. Meadows, J. Randers, D. Meadows, A Synopsis: Limits to Growth: the 30-Year Update, vol. 381, Chelsea Green Publishing Company, Estados Unidos, 2004.

[12] J. Randers, J. Rockström, P.-E. Stoknes, U. Goluke, D. Collste, S.E. Cornell, J. Donges, Achieving the 17 sustainable development goals within 9 planetary boundaries, Global Sustain. 2 (2019).

[13] S. Dixson-Declève, O. Gaffney, J. Ghosh, J. Randers, J. Rockström, P.E. Stoknes, Earth for All: A Survival Guide for Humanity, New Society Publishers, 2022.

[14] W. Steffen, K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sörlin, Planetary boundaries: guiding human development on a changing planet, Science 347 (6223) (2015).

[15] J. Rockström, W. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E. Lambin, T. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, Planetary boundaries: exploring the safe operating space for humanity, Ecol. Soc. 14 (2) (2009).

[16] M. Graymore, Journey to Sustainability: Small Regions, Sustainable Carrying Capacity and Sustainability Assessment Methods, Australian School of Environmental Studies, Griffith University, Brisbane, 2005. Doctor of Philosophy.

[17] M. Khorsandi, S. Homayouni, P. van Oel, The edge of the petri dish for a nation: water resources carrying capacity assessment for Iran, Sci. Total Environ. 817 (2022), 153038.

[18] B. Nazari, A. Liaghat, M.R. Akbari, M. Keshavarz, Irrigation water management in Iran: implications for water use efficiency improvement, Agric. Water Manag. 208 (2018) 7–18.

[19] P. Saemian, M.J. Tourian, A. AghaKouchak, K. Madani, N. Sneeuw, How much water did Iran lose over the last two decades? J. Hydrol.: Reg. Stud. 41 (2022), 101095.

[20] J. Cohen, I. Stewart, The Collapse of Chaos: Discovering Simplicity in a Complex World, Penguin UK, 2000.

[21] M.B. Mesgaran, K. Madani, H. Hashemi, P. Azadi, Iran's land suitability for agriculture, Sci. Rep. 7 (1) (2017) 7670.

[22] M.J.D. Hack-ten Broeke, H.M. Mulder, R.P. Bartholomeus, J.C. van Dam, G. Holshof, I.E. Hoving, D.J.J. Walvoort, M. Heinen, J.G. Kroes, P.J.T. van Bakel, I. Supit, A.J.W. de Wit, R. Ruijtenberg, Quantitative land evaluation implemented in Dutch water management, Geoderma 338 (2019) 536–545.

[23] S. Zekri, Water Policies in MENA Countries, Springer, 2020.

[24] R. Ardakanian, Overview of Water Management in Iran, Water Conservation, Reuse, and Recycling: Proceeding of an Iranian-American Workshop, The National Academies Press, Washington, DC, 2005, pp. 18–33.

[25] P. Azadi, M.B. Mesgaran, M. Mirramezani, The Struggle for Development in Iran: the Evolution of Governance, Economy, and Society, Stanford University Press, 2022.

[26] W. Bank, Managing Economic Uncertainties - with a Special Focus : Preparing for an Uncertain Water Future, World Bank, Washington, DC, 2022. Iran Economic Monitor, Spring 2022.

[27] S. Ansari, H. Dehban, M. Zareian, A. Farokhnia, Investigation of temperature and precipitation changes in the Iran's basins in the next 20 years based on the output of CMIP6 model, Iran. Water Res. J. 16 (1) (2022) 11–24.

[28] E. Rafiei-Sardooi, A. Azareh, S. Joorabian Shooshtari, E.J.R. Parteli, Long-term assessment of land-use and climate change on water scarcity in an arid basin in Iran, Ecol. Model. 467 (2022), 109934.

[29] H. Hamarash, R. Hamad, A. Rasul, Meteorological drought in semi-arid regions: a case study of Iran, J. Arid Land 14 (11) (2022) 1212–1233.

[30] R. Noori, M. Maghrebi, S. Jessen, S.M. Bateni, E. Heggy, S. Javadi, M. Nouri, S. Pistre, S. Abolfathi, A. AghaKouchak, Decline in Iran's Groundwater Recharge, 2023.

[31] M. Negahdary, Shrinking aquifers and land subsidence in Iran, Science 376 (6599) (2022) 1279.

[32] R. Noori, M. Maghrebi, A. Mirchi, Q. Tang, R. Bhattarai, M. Sadegh, M. Noury, A. Torabi Haghighi, B. Kløve, K. Madani, Anthropogenic depletion of Iran's aquifers, Proc. Natl. Acad. Sci. USA 118 (25) (2021), e2024221118.

[33] S. Ashraf, A. Nazemi, A. AghaKouchak, Anthropogenic drought dominates groundwater depletion in Iran, Sci. Rep. 11 (1) (2021) 9135.

[34] M. Darand, F. Pazhoh, Spatiotemporal changes in precipitation concentration over Iran during 1962–2019, Climatic Change 173 (3) (2022) 25.

[35] A. Sharifi, R. Mirabbasi, M. Ali Nasr-Esfahani, A. Torabi Haghighi, R. Fatahi Nafchi, Quantifying the impacts of anthropogenic changes and climate variability on runoff changes in central plateau of Iran using nine methods, J. Hydrol. 603 (2021), 127045.

[36] A. AghaKouchak, A. Mirchi, K. Madani, G. Di Baldassarre, A. Nazemi, A. Alborzi, H. Anjileli, M. Azarderakhsh, F. Chiang, E. Hassanzadeh, L.S. Huning, I. Mallakpour, A. Martinez, O. Mazdiyasni, H. Moftakhari, H. Norouzi, M. Sadegh, D. Sadeqi, A.F. Van Loon, N. Wanders, Anthropogenic drought: definition, challenges, and opportunities, Rev. Geophys. 59 (2) (2021), e2019RG000683.

[37] S.-M. Hosseini-Moghari, S. Araghinejad, K. Ebrahimi, Q. Tang, A. AghaKouchak, Using GRACE satellite observations for separating meteorological variability from anthropogenic impacts on water availability, Sci. Rep. 10 (1) (2020), 15098.

[38] S. Shadkam, Preserving Urmia Lake in a Changing World : Reconciling Anthropogenic and Climate Drivers by Hydrological Modelling and Policy Assessment, Wageningen University, Wageningen, 2017.

[39] M. Salman, M. García-Vila, E. Fereres, D. Raes, P. Steduto, The AquaCrop Model–Enhancing Crop Water Productivity: Ten Years of Development, Dissemination and Implementation 2009–2019, Food & Agriculture Org, 2021.

[40] L.H. Gunderson, C.S. Holling, Panarchy: Understanding Transformations in Human and Natural Systems, Island Press, Washington, DC, 2002.

[41] C.S. Holling, Understanding the complexity of economic, Ecol. Soc. Syst. Ecosyst. 4 (5) (2001) 390–405.

[42] M.M. Waldrop, T. Wilbanks, et al., Complexity: the Emerging Science at the Edge of Order and Chaos, Viking, London, 2003.

[43] R.W. Shephard, Proof of the law of diminishing returns, Z. für Natl. 30 (1) (1970) 7–34.

[44] E. Cannan, The origin of the law of diminishing returns, 1813-15, Econ. J. 2 (5) (1892) 53–69.

[45] M. Javidan, A. Dastmalchian, Culture and leadership in Iran: the land of individual achievers, strong family ties, and powerful elite, Acad. Manag. Perspect. 17 (4) (2003) 127–142.

[46] E. Tucker, in: Nikki R. Keddie, Rudi Matthee (Eds.), Iran and the Surrounding World: Interactions in Culture and Cultural Politics, University of Washington Press, Seattle and London, 2002, pp. 108–114. ISBN 0-295-98206-3, notes, xv+ 393 pp, Iranian Studies 39(1) (2006).

[47] C. Madrid-López, M. Giampietro, The water metabolism of socio-ecological systems: reflections and a conceptual framework, J. Ind. Ecol. 19 (5) (2015) 853–865.

[48] M. Giampietro, K. Mayumi, J.R. Martín, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MUSIASEM): an Outline of Rationale and Theory, Universitat Autònoma de Barcelona. Departament d'Economia Aplicada, 2008, p. 1. Working papers.

[49] A. Koocheki, M.N. Mahallati, S. Khorramdel, Ecological foodprint of Iran, Agroecol. Sustain. Food Syst. 40 (5) (2016) 493–515.

[50] M. Fatemi, K. Rezaei-Moghaddam, M. Wackernagel, C. Shennan, Sustainability of environmental management in Iran: an ecological footprint analysis, Iran Agric. Res. 37 (2) (2018) 53–68.

[51] J. Zhang, Z. Dong, Assessment of coupling coordination degree and water resources carrying capacity of Hebei Province (China) based on WRESP2D2P framework and GTWR approach, Sustain. Cities Soc. 82 (2022), 103862.

[52] P.D. Ditlevsen, S.J. Johnsen, Tipping points: early warning and wishful thinking, Geophys. Res. Lett. 37 (19) (2010).

[53] C.L. Franzke, A. Ciullo, E.A. Gilmore, D.M. Matias, N. Nagabhatla, A. Orlov, S.K. Paterson, J. Scheffran, J. Sillmann, Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling, Environ. Res. Lett. 17 (1) (2022), 015004.

[54] M. Gladwell, The Tipping Point: How Little Things Can Make a Big Difference, 2000.

[55] E.H. van Nes, B.M. Arani, A. Staal, B. van der Bolt, B.M. Flores, S. Bathiany, M. Scheffer, What do you Mean,'Tipping point, Trends Ecol. Evol. 31 (12) (2016) 902–904.