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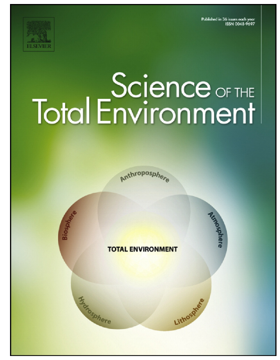

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The edge of the petri dish for a nation: Water resources carrying capacity assessment for Iran

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Abstract

Different methods have been proposed in population dynamics to estimate carrying capacity (K). This study estimates K for Iran, using three novel methods by integrating land and water limits into assessments based on Human Appropriated Net Primary Production (HANPP). The first method uses land suitability as the limiting resource. It gives theoretical estimates for K. The second method which is based on the first method, uses land suitability and water resources availability as limiting resources assuming highly efficient agriculture, also resulting in theoretical estimates for K. The third method is based on the second method assuming a lower, more realistic agricultural efficiency. The third therefore results in more realistic estimates. Four spatial hydrological scale levels were considered to estimate food production. Also, nine scenarios were defined: a reference one reflecting the current situation, five others for the first method, two for the second method, and finally, one scenario for the third method. Results show severe limitations on food production by the availability of suitable land, water availability, and crop productivity for agriculture. We estimated theoretical values for K using land and water limiting resources separately. Two realistic scenarios considering realistic agricultural productivity and water use at national and local levels were assessed, resulting in 35.5 and 20 million people, respectively. These are alarming values compared to the current population of Iran (84 million). Moreover, our conservative estimations are still higher than any assessment

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when considering social, economic, or political barriers. This research provides a systematic analysis of carrying capacity in Iran, showing the importance of food import on Iranians' lives, relevant to land, water, and food policies.

Key Words: Carrying Capacity, Google Earth Engine, HANPP, Iran, Population, Water.

1. Introduction

Human carrying capacity (K) is the number of people supported sustainably within a region constrained by natural resource limits and human choices, including social, cultural, and economic conditions (Franck et al., 2011). Different methods exist to estimate K, at any scale (Cohen, 1995). Cohen classified these methods into six categories, and most of them focus on limiting factors and Liebig's Law of the Minimum (Cohen, 1995). The limiting factor of these methods progressed from only ecological ones to include social constraints (De Wit, 1967; Fremlin, 1964; Hardin, 1968; Kleiber, 1961). For example, Kleiber (1961) modeled K based on embodied carbon in the human body as the limiting factor, while De Wit (1967) estimated K at a global scale based on terrestrial photosynthetic productivity. After Meadows et al. (1972), scholars started to combine ecological and social processes into coupled models to show the limits to growth (Meadows et al., 1972; Meadows et al., 2004). Franck et al.'s (2011) work is one example of this category which used the LPJmL model (a dynamic global vegetation model with a managed planetary land surface) to estimate K, which used plants photosynthesis as the limiting factor. Another example is the EARTH3 model (Randers et al., 2018), which combines the WORLD3 system dynamics (SD)-based model (Meadows et al., 2006) with the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015) to estimate K. Collste et al. (2018) combined and used planetary boundaries as a global biophysical carrying capacity

($K_{Biophysical}$) and SD model for different world regions as social carrying capacity (K_{Social}). However, at the local scale, there are fewer studies (Graymore, 2005; Lane, 2014; Lane et al., 2014).

There is a primary dynamic limiting factor for growth in each social and ecological component (De Leeuw et al., 2019; Lubell and Niles, 2019). These social and ecological components are dynamic over time. However, they also have complex adaptive interactions as a complex adaptive system (CAS). The social-ecological system (SES) is a branch of CAS with an emphasis on "Social" and "Ecological" components with their complex interaction (Biggs et al., 2012). Some scholars used the (t) index to emphasize temporal dynamics for K assessment (Lane, 2014). Consequently, K, the output of an SES, has a complex dynamic value over time (Lane, 2014). In addition, it is helpful to separate biophysical and social parts as $K_{Biophysical}(t)$ and $K_{Social}(t)$ respectively. The overall K can be formulated as a function of both as:

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

where $f()$ is the representative of the SES system and $K(t)$ is its output. The $K_{Biophysical}(t)$ is a limit of the population which the resources of a region can support at a specific level of food production technology to provide human needs. While the $K_{Social}(t)$ is the sustainable population number using a given social organization (Franck et al., 2011). $K_{Social}(t)$ is always less than $K_{Biophysical}(t)$ (Lane, 2014), thus it makes sense to say that in a sustainable society, $K_{Biophysical}(t)$ is the upper limit for the social one (Franck et al., 2011). In an unsustainable way, the population can surpass $K_{Social}(t)$, $K_{Biophysical}(t)$, or $K(t)$ which cause the overshoot and collapse behavior for the population in the long term with a decreased $K(t)$ (Meadows et al., 2006).

Food is the ultimate limiting factor for the human population and its carrying capacity (Porkka et al., 2017). The main food source available in nature is gross primary productivity (GPP) minus plant respiration, namely net primary productivity (NPP). The human appropriation of net primary production (HANPP) is one of the integrated socioecological indicators which quantifies available biomass for human needs. In this regard, the HANPP values can be upper limits for $K_{Biophysical}(t)$. Importing food and materials helps to push local limits to growth (Porkka et al., 2017). Importing can be financed by revenue from oil/gas export. Based on Van Oel et al. (2009), the related virtual water transfer behind it can be quantified (Figure 1a).

Iran is one of the world's leading oil exporters, facing severe water bankruptcy (Madani et al., 2016). The high population is one of the main drivers of the water crisis in Iran (Madani, 2014). For Iran, suffering from global sanctions, trade isolation because of banking limits, and self-sufficiency voice by its decision-makers, the import and export is low or at least not reliable. On the other hand, the ever-increasing demand in the global food market and higher purchasing power by other countries than Iran (mainly when international sanctions impose limits on Iran's oil export) force Iran to use internal resources to feed its own people. The sustainability of the food provision for this complex situation is not easily quantifiable. A more accurate estimate for K is needed for a better policy. Some references (Graymore et al., 2010; Lane, 2014) recommend local food production as a recipe for sustainable food production. This situation for this case can be depicted in Figure 1b. Therefore, in this study, we are interested in the assessment of $K_{Biophysical}(t)$ for Iran with rising this question: "*How many people can be fed in Iran as a water-scarce country in a self-sufficient manner?*"

Although HANPP was used globally, we use this concept for national and small-scale analysis in a novel way to study water resources carrying capacity considering self-sufficiency limit. Also, several studies have been done in Iran focused on just one aspect of food production using geospatial data (Mesgaran et al., 2017; Maghrebi et al., 2020; Ghorbanian et al., 2020; Gumma et al., 2017; Karandish, 2021), or water crises (Sharifi, 2021; Noori, 2021; Madani, 2016, Madani, 2014) however, none of them included carrying capacity assessment. This research is the first one in Iran and can inform the population and land use planning using a novel scientific method and the most up-to-date remotely sensed global data. Our new method combines multiple natural limits (namely suitable lands for agriculture, water, and HANPP) concisely and coherently, making it easily applicable in other areas.

2. Materials and Methods

The specific steps of this research include: (1) Defining scenarios, (2) Methodology implementation, (3) Introducing case study and data curation, (4) Calculation of available water at different spatial scales, (5) Calculation of agriculture land suitability, (6) defining food requirements relationship with HANPP, and (7) showing the dynamic between population and K in longterm. The implementation of different method sections was described in detail in Section 2.2.

2.1. Scenarios

For each spatial scale explained in Section 2.6, nine different scenarios were developed according to Table 1. These scenarios numbered from 1 to 9, showing different K values from the most theoric and unsustainable one (Scenario 1) to the current situation (Scenario 9). We assumed optimistic assumptions for climate and social situation in these nine scenarios, which means no drastic change in water resources because of climate change or drought and no economic/social failure inside the country. Our social assumption means there is no problem with trading the food and material from a place to another one inside Iran. These assumptions consider that the technology has grown so much that a unit of surface area can produce calories without considering the uncertainties of pests, accidents, or floods when cultivated. For Scenarios 1, 3, 4, 5, and 6, the only constraint is suitable lands (SI), according to Table 1. For Scenarios 2, 7, and 8, water resource is regarded as the central limit, and SI as another constraint (e.g., cultivated lands based on SI) is calculated based on available water at each study unit. Scenarios 2 and 7 treat the water limit at the national scale, while Scenario 8 treats it at the local scale. Scenarios 7 and 8 consider 25% of NPP as the constraint for agriculture efficiency. Need to mention that agricultural efficiency is theoretically unlimited for Scenarios 1-6. Scenario 9 shows the current situation of Iran agricultural lands based on high-resolution (10m) landcover as the reference scenario. The detail of these scenarios is presented in Table 1. We estimated the K value for Scenario 7 after collapse using landcover data for 2020. The K value after the collapse for Scenario 8 was considered equal to the K value for Scenario 4.

2.2. Method implementation

We assessed Iran's carrying capacity using three limits, namely: (1) agriculture land suitability, (2) water, and (3) agricultural efficiency. First, we replicate Mesgaran et al.'s (2017) work to produce agricultural land suitability. For this reason, available global geographic information system (GIS) databases and the Google Earth Engine (GEE) platform were used. The water data provided by the Iran Ministry of Energy (MOE) were then used to calculate the Maximum Level of Water Consumption ($MLWC$) based on the water cycle (Appendix A, Figure A1) at different spatial levels (Appendix A, Figure A2). Then for each study unit at different scales, a balance between available water and actual evapotranspiration (AET) was identified. The method for this balance is based on the total AET from lands with SI more than a threshold ($SI_{Balance}$). This

$SI_{Balance}$ threshold was found for each hydrological region of interest (HROI) in a trial and error manner. The trial and error method used AET calculation in GEE. AET was calculated for lands with SI above a SI threshold using TerraClimate datasets. This relationship is linear for SI values smaller than 0.4 for all scenarios (Figure 2). The $SI_{Balance}$ value was found by solving the equation $AET = MLWC$ (Figure 2). Then for the $SI_{Balance}$ value, the high-quality agricultural areas were identified where $SI > SI_{Balance}$. Using the method presented by Franck et al. (2011), we can calculate the highest K value for each study unit.

More realistically, the K value in the long term can be calculated using HANPP in that area and per capita human consumption. In the end, we calculate the yearly time series for K using HANPP [e.g., $K(t)$] to see the dynamic of primary food production in the area. The current agricultural lands and AET were also calculated using ESRI landcover maps (Karra et al., 2021) to see the level of water consumption for agriculture and the phantom carrying capacity in that area. This overall flowchart is presented in Figure 3.

2.3. Case Study

With an area of 1,648,195 km^2, Iran is the 18th largest country globally and, with 84 million inhabitants, is the 19th most populous country in the world. Iran lies between 24° to 40°N and 44° to 64°E. This second-largest country in the Middle East 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 1770 km) to the south, Afghanistan to the east and Pakistan to the southeast (Figure 4). It is covered by two large mountain chains, Zagros from northwest of the country south-eastward to the Persian Gulf and Alborz from the northwest to the east along the Caspian Sea. Iran's surface water and groundwater are limited, while the geographical distribution of its water supplies and water demands are highly heterogeneous. The annual precipitation ranges from less than 50 mm in the central parts to more than 1600 mm in some northwest coast of the Caspian Sea. Iran includes six main drainage basins, 30 main sub-basins. These main sub-basins were then divided into 609 water study areas based on topography and the location of aquifers.

2.4. Population Data

Iran population long-term historical data and future projections were shown in Figure 5 were extracted from the United Nations Department of Economic and Social Affairs (UN-DESA). These future population projections also provide upper and lower values for population predictions using +0.5/-0.5 values for total fertility rates (TFR) with 80% and 95% confidence intervals.

2.5. Geospatial Data

Based on the provided flowchart in Figure 3, geospatial data and layers were collected from multiple sources. These data sources include 16 sets of data, including land cover (10 m resolution), soil properties (30″ ×30″ horizontal resolution), topography (30 m resolution), climate (~5 km resolution), and MODIS-NPP product (250 m resolution). GEE platform was used to perform all spatial analyses. The detailed information for data used and their descriptions, including data sources, are in Appendix A, Table A1. Although multiple studies have used geospatial data on Iran, to our knowledge, almost none has investigated carrying capacity.

2.6. Water resources availability

The amount of available water is based on the Iran MOE studies. Their way of calculating available water is based on renewable water and estimating different parts of the water cycle at different spatial scales in the long term. There is one or more HROI at each spatial level. For each HROI, the water cycle can be shown using 23 variables in Appendix A, Figure A1. In this way, the maximum water consumption is:

$$MLWC_{HROI} = X17_{HROI} - X21_{HROI} \quad (2)$$

where: $MLWC_{HROI}$ = Maximum level of water consumption at HROI; $X17_{HROI}$= Net water consumption at HROI, and $X21_{HROI}$ = Excessive water use at HROI.

This level of water allocation for agriculture means converting all possible blue water to green water using land-use change and irrigation by humans (Falkenmark, 2008). Water allocation less than this means keeping water in surface and groundwater reservoirs as environmental flows. Also, higher water allocation means a reduction in base flow requirements for ecosystem functions or groundwater drawdown (Coates et al., 2013).

As study units with a physical hierarchy and delineation of watersheds, the HROIs are shown in Appendix A, Figure A2. Those are at:

- National level (L0, the number of watersheds is 1),
- Main basins level (L1; the total number of watersheds are six, numbered using single-numbers from 1 to 6).
- Main sub-basins level (L2; the number of watersheds is 30, from 11 to 60. The first digit is inherited from Main basins, and a second digit is a counter number for sub-basins in that main basin).

- Study areas based on Iran's MOE (L3; with 609 watersheds, numbered with four-digit numerals from 1101 to 6013. The first two digits are inherited from the Main sub-basins. The other two digits are counter numbers for study areas in that main sub-basin).

2.7. Land suitability

This step provides the extent of the lands which are suitable for agriculture or producing HANPP. In core, this part is the replication of Mesgaran et al. (2017)'s work, with finer and more up-to-date data sources. For this reason, we need to overlay several geospatial information layers and calculate the SI map and the extent of its classes, as shown in Appendix A, Table A2. These layers are presented in Appendix A, Table A1. The suitability index is defined to transform the value for soil, water, and topography to a 0 to 1 scale.

$$S(V) = \begin{cases} 0 & Var \leq V_{min} \\ \dfrac{Var - Var_{min}}{Var_{ol} - Var_{min}} & Var_{min} < Var < Var_{ol} \\ 1 & Var \geq Var_{ol} \end{cases} \quad (3)$$

where $S(V)$ = suitability index as a function of each variable (Var); V_{min} = indicates the minimum value of Var for crop growth; Var_{ol} = the lowest optimum value of Var at or beyond which the highest suitability can be obtained. Mesgaran et al. (2017) can find these parameters for each variable.

2.8. Food as the limiting factor for carrying capacity assessment

De Wit (1967) was the first to estimate K using photosynthesis as the limiting factor (Franck et al., 2011). As Franck et al. (2011) showed, their assumption was very efficient agriculture. In this case, the K can be calculated in the following way. K is total available food divided by per capita food requirement. The total dried matter production by photosynthesis can be calculated as:

$$PP = A.h \quad (4)$$

where PP = photosynthesis production (Kg); A = productive area (m^2); and h = harvest per unit of area (Kg/m^2 or kcal/m^2). For a non-uniform landscape (A), this Equation should be written as:

$$PP = \iint_A h(x,y)\, dA \quad (5)$$

where $h(x,y)$ = harvest function for each landscape point (Kg/m^2).

An estimation of per capita nutritional food (n) is also required to calculate K. There are multiple sources for this value which reported values from 2100 kcal/day for India to 3500 kcal/day for the United States. Walter Willett et al. (2019) recommended a 2500 kcal/day intake for a sustainable healthy diet in the Anthropocene considering planetary boundaries and sustainable food systems. With awareness of regular diet in Iran, the level of waste, and the lack of sustainable food systems, this number is different. According to the "FAO Food Consumption Nutrients spreadsheet" (Leclercq et al., 2019), Iranian calorie intake over time is in Appendix A, Table A3. We considered 3,000 kcal/day/person for each Iranian citizen for this research. In this way, K based on the available calorie in HANPP can be calculated as Equation (6).

$$K = \frac{A.h}{n} \quad (6)$$

where n = per capita food requirement (kcal/day/person). Franck et al. (2011) correctly mentioned that more than productive land, each citizen needs some area in the form of infrastructure (B) (house, roads, recreation, etc.), which would not be available for production and agriculture. De Wit (1967) calculated this number as 750m^2 at its lowest value in the US. His value was derived from the densely populated region between Boston and Washington DC. In a more realistic scenario, they considered 1500m^2 value (Franck et al., 2011). This value range for Iran was calculated and presented in Appendix A, Table A4. In this way, the K value can be estimated as Equation (8) (Franck et al., 2011):

$$K = \frac{A.h}{n} - \frac{K.B.h}{n} \tag{7}$$

$$K = \frac{\frac{A.h}{n}}{1 + \frac{B.h}{n}} \tag{8}$$

This estimate of K is based on the subtraction of area B from productive Areas (A). As humans throughout history improved their agriculture and harvesting, the extreme theoretical value for K can be derived by De Wit (1967) highly efficient agriculture where $h \to \infty$ in Equation (9).

$$K_{Theorically\ Maximum} = \lim_{h \to \infty} \frac{\frac{A.h}{n}}{1 + \frac{B.h}{n}} = \frac{A}{B} \tag{9}$$

In this paper, we calculated this theoretical K at four spatial scales mentioned in Section 2.6 "L0, L1, L2, L3" with six SI thresholds "0, $SI_{Balance}$, 0.2, 0.4, 0.6 and 0.8" (Scenarios 1-6).

2.9. Suitable and non-suitable lands for agriculture

In section 2.8, two areas were needed to calculate the maximum theoretical K for each region [A and B parameters in Equation (9)]. These two areas can be calculated using the SI map. Areas with SI greater than specific thresholds ($SI_{Threshold}$) based on Mesgaran et al. (2017) are considered suitable for agriculture to calculate (A) areas, and other areas are either excluded areas or will provide land for infrastructures (B) like roads and urban areas.

2.10. Human needs, Food, NPP, and HANPP

Section 2.8 explained how agricultural efficiency or technology could theoretically be perfect and not act like a barrier. However, in reality, there are many limits to agricultural production. We assume that farmers did their best in their lands over time, and the result of human and nature interaction is what happened and can be measured using NPP via satellite imagery. Running (2012) suggested NPP as the measurable planetary boundary for sustainable human activity. The logic behind this suggestion obeys these steps:

- To maintain more people, we need food (You cannot sustain a human without feeding him).
- To produce food, we need to harvest the sun (Sun energy is a limit).
- We can harvest the sun by NPP (The maximum NPP is a limit).
- To increase the NPP, we develop agriculture (Land/Plant productivity is a limit).
- To reach agricultural production, we need inputs, which make a percentage of NPP available for humans called HANPP (NPP to HANPP conversion factor). Agricultural inputs are:
    - Land (Suitable land for agriculture is limited, Section 2.7)
    - Water (Water resources are limited, both renewable and non-renewable, Section 2.6)
    - Plant (Plant productivity for industrialized and high-efficiency plants are limited. Same for indigenous plants, but they are more resilient than others, NPP is its upper limit)
    - Technology (The available technology has its limitations, $\frac{\text{HANPP}}{\text{NPP}} < 1$)

For each step, there is a limit, which is mentioned in the parenthesis. The amount of NPP harvested and converted to food for human use is human appropriated NPP (HANPP). NPP can be appropriated for human use in two possible ways (Haberl et al., 2014): (1) area-specific approach and (2) consumption-based approach. However, the area-specific approach does not consider imported and exported products by the residents outside the study region. This gap was later covered by the ecological footprint approach, which led to proposing and developing embodied HANPP (eHANPP). In this study, by emphasizing assessment under self-sufficiency scenario in each study area and local use of water resources, we use HANPP. Vitousek et al. (1986) estimated the $\frac{\text{HANPP}}{\text{NPP}}$ fraction around 20-30% at the global scale. In a review of HANPP studies, Haberl et al. (2014) confirmed this estimation as a reliable and reasonable estimate. Therefore, this study will use 25% as the appropriated part of NPP by humans at all spatial scales in Iran. The considered HANPP is the upper limit for the sum of NPP_{harv} and NPP_{luc} in the scenario that all harvested HANPP will be used efficiently, and no HANPP will be lost because of land-use change. The terms and concepts around NPP and HANPP can be depicted in Appendix A, Figure A3 (Andersen and Quinn, 2020). Then this HANPP can be converted to food for human consumption. De Wit (1967) used the Equation that each gram of carbohydrate in HANPP can provide four kcal of energy for human consumption.

2.11. Overshoot and collapse

Overshoot and collapse is a reference mode to study the unsustainable population growth behavior in the long term (Mirchi et al., 2012). Mann (2018) classified different perspectives around population dynamics in a spectrum from William Vogt's idea (Extreme pessimist) to Norman Borlaug's idea (Extreme optimist). Mann (2018) concluded that both groups and the spectrum in between inform us of current or future limits on the human population. These limits can be social or ecological. Therefore, it is possible to note the limiting factor for some of them (Appendix A, Figure A4). However, an imaginary (or semi-physical) variable will emerge by implementing all limiting variables in an SES system, which is "Carrying Capacity" or K (Appendix A, Figure A5).

K, in this sense, is the Malthusian or Vogtian variable (Vogt, 1949) of a landscape. It assumes the population of an area can grow faster than its balance with nature which can cause population overshoot and collapse, and also the erosion of K (Hardin, 1968). This overshoot and collapse dynamic is our scientific guess that we will test by comparing K estimates with population data.

3. Results

3.1. Land suitability map

The land suitability index map for the whole country was calculated using geospatial data (Appendix A, Figure A6). This suitability map is based on soil, climate, and topography criteria; nevertheless, it does not consider the available water explicitly. The linear relationship between the SI threshold and $MLWC$ was calculated for this goal. The SI threshold is graphically presented at the national level in Appendix A, Figure A7. However, this value was calculated for each HROI. The value for the SI threshold at the L0 scale is equal to 0.074, which was based on linear interpolation of different SI values versus the AET from the lands with SI higher than those values. These potential lands for cultivation with SI > 0.074 are shown in Appendix A, Figure A8a, which are maximum arable lands at the national level, considering sustainable water availability. At this ideal balance between AET of suitable lands and national $MLWC$, the total area of these lands is 195304.954 km^{2}, and the total AET from them is 62.637 BCM.

Appendix A, Figure A8e shows the current extent of agricultural areas in Iran (Karra et al., 2021). The total area of these croplands is 148,433.807 km^{2}, and the total AET from those lands is 55.285 BCM. The resulting values between ideal balance and reality observed areas in 2020 are very similar. This similarity means that at the national level, Iran uses the maximum amount of water it has for its agriculture with the price of cultivating its poor-quality lands for agriculture. At the same time, if they could have more water at the national level, they would expand agriculture on more lands with $0 < SI \leq 0.074$ in a very unsustainable manner.

However, considering the spatial variability of water resources, the SI threshold should be calculated geographically, suitable lands with this water limitation, and their AET. Therefore, the same approach was applied for main basins, sub-basins, and study areas (Appendix A, Figures A8a b, c, d).

3.2. Maximum theoretical water resources self-sufficient carrying capacity

The maximum theoretical carrying capacity using B = 1500 m^2 for each HROI are shown in Table 2, and more detailed results in Tables A5-A7 in Appendix A. Table 2, column (1) shows the result of K assessment for Scenario 2, using water availability at different scales (L0, L1, L2, and L3). As expected, when K is estimated at the local scale (Scenario 2, Column 1, L3), it can reflect the highest level of local self-sufficiency. It means there is no water trade with the country's other regions. At this level, the total K for the whole country (sum of K values for 609 study areas) is 76.75 million people. On the other hand, calculating K for the whole nation (Scenario 2, Column 1, L0) indicates the lowest local self-sufficiency by effective water trade inside the country without any economic limits. This value is 130.2-million people.

3.3. Water resources carrying capacity using HANPP

This estimation using HANPP is more realistic than previous theoretical values for K since the maximum theoretical assessment assumes unlimited agriculture productivity (or, in another way, infinite crop per drop). Consequently, the K value for different scales was calculated using

HANPP and 3000 kcal/day/person food requirements (Table 2, column 2). Table 2 shows the result of the K assessment using water availability at different scales (Scenarios 7 and 8). When K was estimated using national water availability (Scenario 7), it showed the highest level of water transfer inside the country. In this scenario, K is 35.5 million people.

On the other hand, using local water availability for food production (Scenario 8) shows the lowest level of water transfer and highest self-sufficiency. In Scenario 8, the total K for the whole country (sum of K values for 609 study areas) is 20.2 million people. All above calculated values for K are presented in Table 3 and Figure 5 based on scenario numbers. They show population overshoot of the carrying capacity for long-term K assessments and theoretical K assessments in Scenarios 3-9.

3.4. Overshoot and collapse

Iran population dynamics, UN-DESA predictions for population, and our results for K show an overshoot and collapse behavior in population and erosion of K (Figure 5). Our results show the 35.5 million people for "long-term HANPP based national scale self-sufficient carrying capacity in Iran" (Figure 5). In this scenario (Scenario 7), the water resources limit is considered at the national level. It means if Iran's internal trade works perfectly and with the amount of oil money they have, there would not be an internal trade problem, and water will exchange as internal water footprint using hidden virtual water transfer. The current estimation of K using high-resolution ESRI landcover for 2020 (Scenario 9) showed the tendency of Iran to use its highest potential for self-sufficiency. This result was confirmed using MODIS-NPP data for 2001-2020 (Figure 5). This trend makes sense since US sanctions, global oil market, and environmental issues made radical ideologic diplomacy of Iran to spend oil money on agriculture and subsidies to produce more food at the price of water and land resources.

4. Discussion

Iran suffers an imbalance between population, resources, and imported/exported food. Madani (2014) predicted three drivers for the looming water crisis in Iran as (1) population growth and distribution, (2) inefficient agriculture, and (3) mismanagement and desire for development. Although the population is a significant driver for this looming crisis, there was no previous study to quantify the population impact on the water crisis in Iran. This study answered this vital question for Iran for the first time, using the edge of scientific knowledge method, new data sources, and considering water resources limits.

Ali Rezagholi, one of the Iranian scholars, reported Iran's K about 7-8 million people for the pre-modernization period (Mergen, 2015). That estimation was based on historical studies (Issawi, 1971; Katouzian, 1981), which was possible thanks to groundwater consumption by roughly 22,000-33,000 qanats (Wulff, 1968). In another study, Bookers and Hunting consultants (1975) predicted Iran's maximum self-sufficient K as 42 million people. They also mentioned:

> *"… with our predictions, self-sufficiency in agriculture in Iran is not possible, and Iran has to import food from outside … Iran can be self-sufficient in producing wheat if they continue importing meat and vice versa*".

Like many other countries, Iran's central policy to tackle feeding its people was, and still is, to import food. Porkka et al.'s (2017) analysis for Iran shows the post-trade carrying capacity phase (Appendix A, Figure A9a). As one of the world's leading oil and gas exporters, Iran compensated for this gap by exporting oil and importing food and other necessities. Porkka et al.'s prediction on Iran's situation is probably correct, which means Iran is fulfilling the gap of its local carrying capacity with its population with two strategies: (1) importing food, (2) putting more pressure on local non-renewable, non-sustainable resources. Their study says Iran was experiencing a "Within local carrying capacity" phase for most of the 20th century and, during the 21st century, entered the "Post-trade carrying capacity" phase. Their results are different from the results of our research using HANPP. The present study showed Iran was experiencing the "Post-trade carrying capacity" phase during the 20th century and is experiencing the "Exceded post-trade carrying capacity" phase during the 21st century (Appendix A, Figure A9b).

Globally, the gap between population and available water was correctly addressed (Falkenmark and Lindh, 1974; Falkenmark et al., 2019). Like many other countries, Iran used a hydraulic mission approach (Conker & Hussein, 2019) to increase its water supply at any price in an unsustainable manner. Wulff (1968) mentioned, in 1968, qanats provided 75% of water use in Iran. Modern water resources development by digging wells during 1968–1979 increased this amount of water unsustainably (Moridi, 2017; Saatsaz, 2020). This trend continues, which causes severe falls in groundwater levels (Saatsaz, 2020). On the other hand, by constructing big dams between 1959 and the present day, the water withdrawal from freshwater resources has reached 88.5 BCM (out of 124 BCM) with almost no potential for increase. However, there is no previous study to show the impact of water developments on filling the gap between population and K; also, there is no study in Iran to show the impact of natural resources overexploitation on K erosion. Our estimation of 35.5 million people for K is based on 61.6 BCM freshwater, the maximum level of sustainable available water provided by MOE. This water gap (61.6 - 88.5 = -26.9 BCM) has been the result of the self-sufficiency movement in Iran since 1988, and it is the core reason for basin closure on surface water and drawdown in groundwater (Ashraf et al., 2019; Ashraf et al., 2021; Moridi, 2017; Moshir Panahi et al., 2020; Saatsaz, 2020).

From a water resources perspective, the primary pressure is now on groundwater resources, previously confirmed by Ashraf et al. (2021). Also, Dalin et al. (2017) showed that while Iran's food import does not cover its internal food consumption, it is one of the leading groundwater exporters via international trade. This embedded groundwater export, together with subsidized energy for the water sector, agricultural incentives, and the driver of the population, caused a problematic situation in groundwater depletion (Ashraf et al., 2021; Forootan et al., 2014; Noori et al., 2021). In this chaos of mismanagement with severe surface/groundwater resources limitations, drought is one of the intrinsic characteristics of Iran that seriously impacts surface water resources (Moshir Panahi et al., 2020). More than that, several studies showed a long-term reduction in water resources due to climate change effects on drylands (Huang et al., 2017) and especially Iran (Abbaspour et al., 2009; Afshar and Fahmi, 2019; Ashraf et al., 2019; Hashemi, 2015; Mansouri Daneshvar et al., 2019; Moshir Panahi et al., 2020). These predictions show a worsening impact on surface water resources reduction by losing water melted from mountainous areas (Viviroli et al., 2011). Since the present study does not cover climate change or drought impacts, it is optimistic about Iran's current reality. However, our results can provide a sense of the present urgent situation for Iran's decision-makers to understand the impact of natural limits on Iran's national economy even by using all the resources.

Other preventive approaches have also been implemented to reduce the gap between K and population. For example, after Iran's 1956 census, the population control policy began seriously. As a result, Iran's total fertility rate has decreased from ~7 in 1960 to 2.15 at present. After two decades of successful implementation, this policy did not continue during 1981-1988 (Iran-Iraq war) and 2013-now (Roudi et al., 2017). However, based on our findings, the population was always beyond Iran's local carrying capacity. This overshoot of K could also be because of a lack of knowledge, not acknowledging the natural limits in Iran. Overpopulation and ignorance with regard to natural limits are not unique to Iran; many other countries similarly deal with this wicked problem (Alcott, 2010; Creanza et al., 2017; Vollset et al., 2020). Focusing on limited water resources, many countries, especially in the Middle East, are dealing with this long-term issue (Mirzaie-Nodoushan et al., 2020; Porkka et al., 2017; Siderius et al., 2020).

It should be highlighted that if Iran's policymakers decide to change their attitude towards a more sustainable manner, it means a local-based food chain using local basin-scale water management and the highest dependency on food import. In this scenario, the "long-term local scale self-sufficient carrying capacity in Iran" based on basin-scale water availability is 20 million people (Scenario 8). Overall, considering either 42, 35.5, or 20 million people as K for Iran, the actual population has passed all of them. As overshoot happened already, we predict an inevitable collapse afterward. The new value for sustainable K would be even less than 20 million since this country has lost lots of its groundwater due to land subsidence (Motagh et al., 2008), lots of its land due to desertification (Cao et al., 2015), a considerable amount of surface water due to climate change and drought (Ashraf et al., 2019; Ashraf et al., 2021), lots of opportunities due to lack of social capacity building, and mismanagement in agriculture (Madani, 2014). Our results suggest this new local K value after the collapse of around 11.5 million people based on medium and good-quality lands for agriculture ($SI > 0.4$) considering uncertain availability of water and suitable lands for Iran in Anthropocene (Figure 5, Scenario 8 after collapse).

4.1. Is there any solution?

Iran's case is a microcosm of the food-water-energy nexus facing the whole planet. Many studies worked on carrying capacity at the planetary level. As Mann (2018) addressed correctly, there is a spectrum of perspectives from the extreme pessimist to the extreme optimist towards the population issue at the global scale as a closed system. Iran as a country is not a closed system, and the first typical solution would be working of purchase power and food import (Porkka et al., 2017). The question would be: 'What should be the level of this food import?', which does not fall within the objectives of this study. On the other hand, if Iran continues its radical policies indicating self-sufficiency and international isolation, the situation for more than 50 million of its inhabitants would be catastrophic. Without a radical shift in people and government behavior around food security and diet, the current scenario (Scenario 9) can have severe social and ecological impacts at any scale.

4.2. Data Uncertainty

Our analyses and results rely on the quality of four primary datasets: NPP satellite product, SI layer, TerraClimate, and $MLWC$. With everyday improvement in spatial data, these datasets are improving. Using Landsat satellite observations with 30 m resolution instead of MODIS with 250 m can enhance the quality of the NPP product both spatially and temporally. A similar study in the United States (Robinson et al., 2018) has recently proved the benefits of such high-resolution Earth observations for these analyses. SI layer improvement can be made using more up-to-date and precise data for soil properties.

Furthermore, it is worth mentioning that it is essential to consider plant growth mechanisms as the central part of the system for quantitative land suitability evaluation. Therefore, the SI layer can be improved using the new methodology presented by Hack-ten Broeke et al. (2019) for the Netherlands based on the WOFOST crop growth model. $MLWC$ data published by the MOE considers both the supply and demand sides for water resources at the L3 scale. $MLWC$ estimates are based on long-term climate data and national datasheets for the demand side; New data sources like TerraClimate, one of the high-resolution global datasets based on monthly data, can improve $MLWC$ data quality from the supply side. From the demand side of the water, it is only possible to use modern monitoring systems.

The other source of uncertainty is parameters. Three static parameters were used in our methodology: (1) NPP to HANPP conversion coefficient, (2) HANPP to calorie conversion factor, and (3) calorie consumption per day per person. Although we considered them constants over the years, all these values are dynamic with spatial and temporal variability. Economy, culture, and agriculture efficiency control these parameters. These data-driven uncertainties are inevitable, and there is a knowledge gap for uncertainty assessment of these sources. For this study, the optimistic values were chosen to estimate high levels of K. Nevertheless, in reality, not only are K values lower, but they are posed to multiple sources of uncertainty. One way to decrease/quantify uncertainty is to use monthly/daily data instead of long-term yearly data.

Biswas and Tortajada (2005) mentioned the lack of a universal definition of sustainability and its implementation. Sustainability definition is apparent (Costanza and Patten, 1995): “a sustainable system survives or persists.” Sustainability is the core element of human carrying capacity (Franck et al., 2011), and without it, the term “Human carrying capacity,” with the emphasis on a long-term perspective and in a sustainable manner, is apparent but not necessarily quantifiable. Therefore, the authors of this paper still emphasize that the assessment results are in an extreme situation of exhausting water resources without considering water resources sustainability. Our results show the upper boundary of the actual carrying capacity in a utopian self-sufficient Iran to show the terrifying consequence of the reality under real threats of climate change, drought, mismanagement, and lack of social capacity development.

As a complex, multi-dimensional problem, one of the best ways of handling the water-food dilemma in Iran is adaptation and using the best lessons from other countries. In an adaptation policy to the water/climate crisis, Mesgaran and Azadi (2018) recommended a drastic increase of import policy for food products. Our results showed that even if the water limit can be solved and agricultural productivity will be improved to unlimited levels, two things would dictate the maximum carrying capacity of Iran: agriculture suitable lands and lifestyle using per capita land requirements as the infrastructure. Even in these utopian scenarios and using poor agricultural lands, Iran's arable lands cannot support more than 70 million people thanks to magical technological solutions. Therefore, Iran decision-makers should revise their policies for the projected future population increase to 90-140 million in the 21st century (UN-DESA). They have to take immediate action for the basic needs of the current population using food import and severe internal/international guidelines as previously mentioned by Falkenmark (2008).

5. Conclusions

Any land-use planning needs a quantitative benchmark that considers environmental limits. Water resource carrying capacity strongly relates to food production capacity for water-scarce regions, which is the primary constraint for limits to growth behavior in population dynamics. We quantified K using the HANPP concept under different scenarios considering local and national food self-sufficiencies. By comparing theoretical K-values with more realistic HANPP-based estimations of K, a firm limit imposed by suitable lands for agriculture was found. This constraint becomes worse considering water resources limits and agricultural efficiency. Moreover, compared to K values using food imports, the self-sufficient estimation of K gives the ability to evaluate import-export policies for food security. This evaluation can show the number of people facing the danger of famine or malnutrition or the level of excess pressure on natural resources because of overpopulation.

The carrying capacity gap (K minus population) provides the quantitative analysis of environmental degradations like groundwater drawdown, land-use change, deforestation, land subsidence, and also degradation of water-related ecological services like aquatic biodiversity and surface water storage. HANPP based estimation for K by emphasizing physical parameters provides the upper boundary of other K-estimation methods in an optimistic scenario observable via satellite imagery.

This physical foundation provides a reliable method with a high level of flexibility to improve by using new data sources, new methods, and implementing new monitoring systems more effectively. The need for more refined soil properties data and a finer network for meteorological measurements are acknowledged. Also, the main gap is now on measuring water consumption by end-users using new technologies for new and more precise K estimations.

HANPP is suitable for estimating the carrying capacity gap under the self-sufficiency assumption. However, one limitation of this method is the quantification of food import/export on national short-term carrying capacity. New methods like eHANPP can be used for the carrying capacity assessment under these scenarios.

This study can help shed light on the rationale of population planning in arid-semi arid areas of the world, especially Iran, its potential usefulness for land use planning, and future studies for water-scarce regions of the world. Nonetheless, we also acknowledge that the carrying capacity is just the starting point for land use planning and population studies should be continued by social studies related to people's lifestyles and economics.

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Table 1: Carrying capacity assessment scenarios in this study

Scenario No.	Scenario Name	Land Constraints	Land Food Productivity	Land usage for agriculture sustainability level	Water consumption for agriculture
1	Theoretical K assessment 1	SI > 0.0	∞	Very Poor	-
2	Theoretical K assessment 2	SI > $SI_{Balance}$	∞	Very Poor	The maximum amount of available water at the national level
3	Theoretical K assessment 3	SI > 0.2	∞	Poor	-
4	Theoretical K assessment 4	SI > 0.4	∞	Medium	-
5	Theoretical K assessment 5	SI > 0.6	∞	Good	-
6	Theoretical K assessment 6	SI > 0.8	∞	Very Good	-
7	Long-term HANPP based Maximum K-National self-sufficient	SI > $SI_{Balance}$	25% of NPP	Very Poor	The maximum amount of available water at the national level
8	Long-term HANPP based Maximum K-Local self-sufficient	Varied locally	25% of NPP	Very Poor	The maximum amount of available water at the local level
9	Current situation	-	-	Very Poor	Beyond the maximum amount of available water, especially

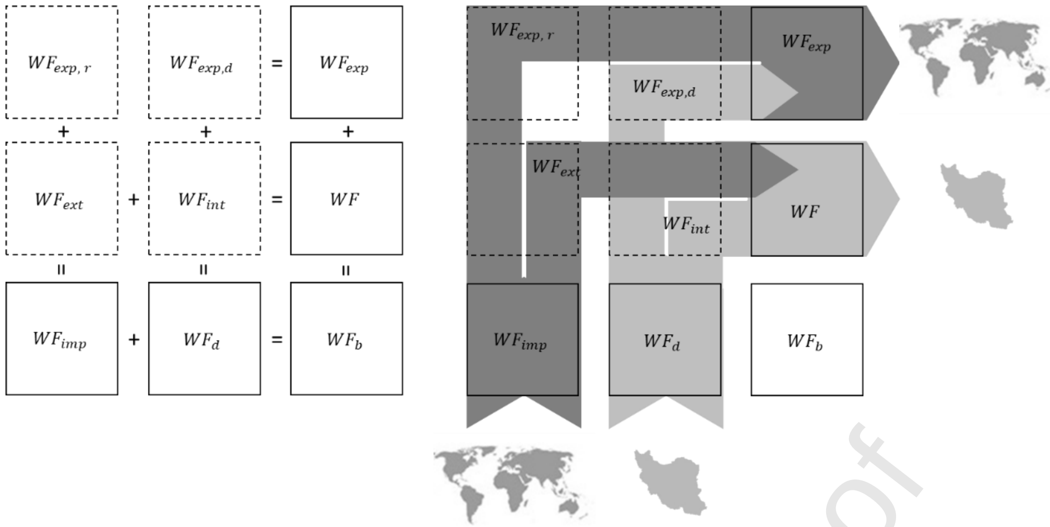
					groundwater

Table 2: (1) The maximum theoretical K and (2) More realistic estimates for K for the whole country using the available water at different spatial scales and $\frac{HANPP}{NPP} = 25\%$. Other important results are provided for the whole country (L0) using the available water at the national level without considering the spatial distribution of water availability, and then sum of regions considering the spatial distribution of water availability at L1, L2 and L3 scales.

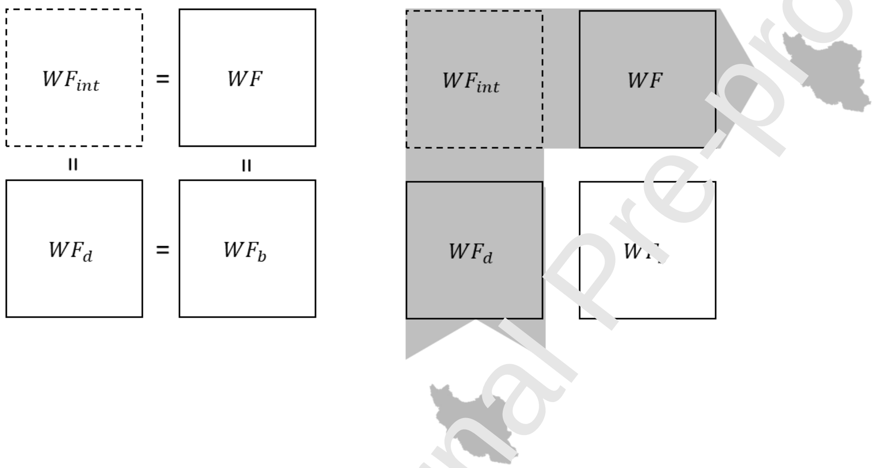
ID	(1) Total maximum theoretical K value (Person)	(2) Total HANPP based K value (Person)	$SI_{Balanced}$	Required land for A at this carrying capacity (km^2)	Available Water (MCM)	AET just from A Areas (MCM)	Croplands Area for 2020 (km^2)	AET for 2020 from croplands (MCM)
L0	130,203,303	35,491,273	0.074	195,304.05	61,619.18	62,636.68	148,433.81	55,274.97
L1 (Sum)	115,279,100	27,697,812	-	172,918.65	61,619.18	52,075.21	148,522.68	55,329.78
L2 (Sum)	98,420,956	24,222,771	-	147,631.45	61,619.18	41,948.78	148,521.87	55,329.76
L3 (Sum)	76,753,332	20,217,020	-	115,130.22	61,619.18	32,803.92	148,519.07	55,329.69

Table 3: Calculated K value for different scenarios

Scenario No.	Scenario Name	Land Constraints	Total ET in BCM (also in % of total water)	Land Food Productivity	Land usage for agriculture sustainability level	Water consumption for agriculture	K-value (Number of people)
1	Theoretical K assessment 1	SI > 0.0	77,417.068 (125%)	∞	Very Poor	-	165,869,730
2	Theoretical K assessment 2	SI > 0.074	62,636.677 (≈100%)	∞	Very Poor	Maximum amount of available water	130,203,303
3	Theoretical K assessment 3	SI > 0.2	34,136.543 (55%)	∞	Poor	-	68,064,206
4	Theoretical K assessment 4	SI > 0.4	6,854.321 (11%)	∞	Medium	-	11,431,186
5	Theoretical K assessment 5	SI > 0.6	1,779.007 (3%)	∞	Good	-	2,591,962
6	Theoretical K assessment 6	SI > 0.8	637.442 (1%)	∞	Very Good	-	868,150
7	Long-term HANPP based Maximum K-National self-sufficient	SI > 0.074	62,636.677 (≈100%)	25% of NPP	Very Poor	Maximum amount of available water	35,491,273
8	Long-term HANPP based Maximum K-Local self-sufficient	Varied locally	32,803.910 (53%)	25% of NPP	Very Poor	Maximum amount of available water needed for available suitable lands locally	20,217,020
9	Current Situation (Year = 2020)	SI > 0.0	55,274,975 (90%)	?	Very Poor	The maximum amount of available water but more pressure on GW because of SW fluctuations with -131 BCM deficit in GW	Current Population = 83,992,953



(a)



(b)

Figure 1: (a) The relationship between imported water footprint (WF_i), domestic water footprint (WF_d), national budget for a water footprint (WF_b) of a country. Water footprint can be divided into two parts: Internal water footprint (WF_{int}) and External water footprint (WF_{ext}). Typically an economy re-exports part of external WF as $WF_{exp,r}$ or part of its dometic WF as $WF_{exp,d}$, (b) Water footprint for a self-sufficient country (or countries without sufficient amount of specific commodities)

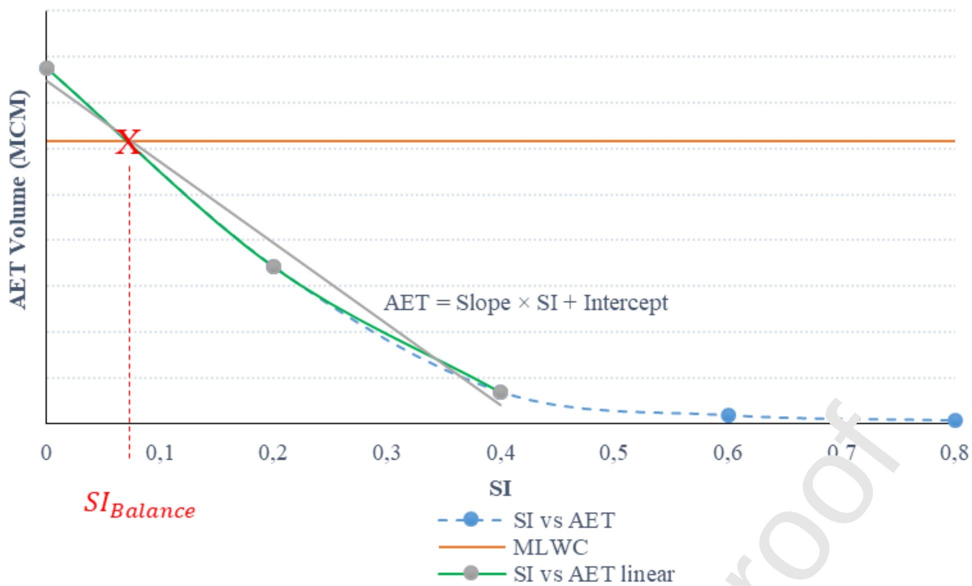


Figure 2: The relationship between AET at different SI intervals and the linear Equation between SI and AET for SI thresholds less than 0.4. The value $SI_{Balance}$ is the intersection of AET and MLWC at that study unit.

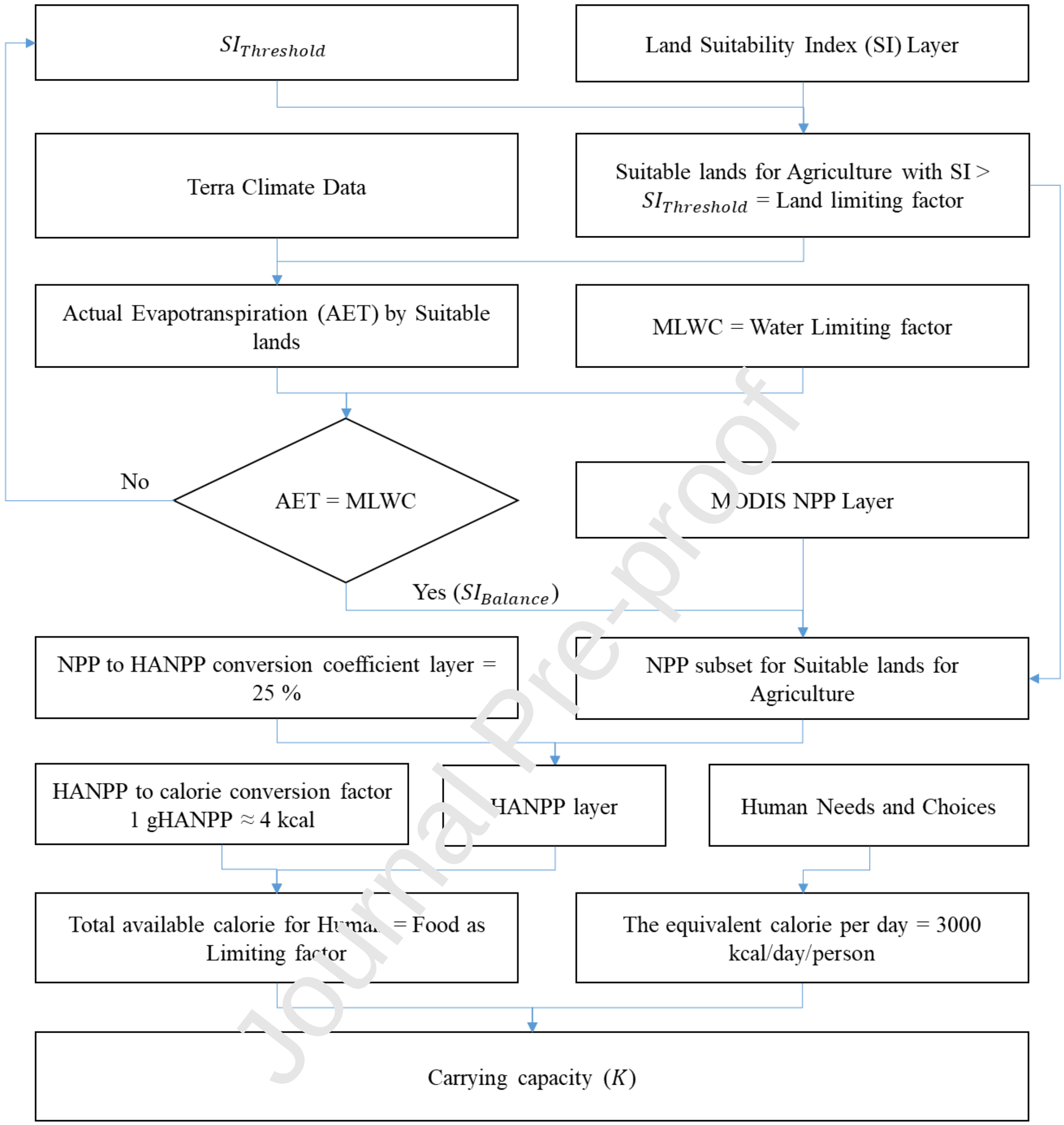


Figure 3: Overall flowchart for this study

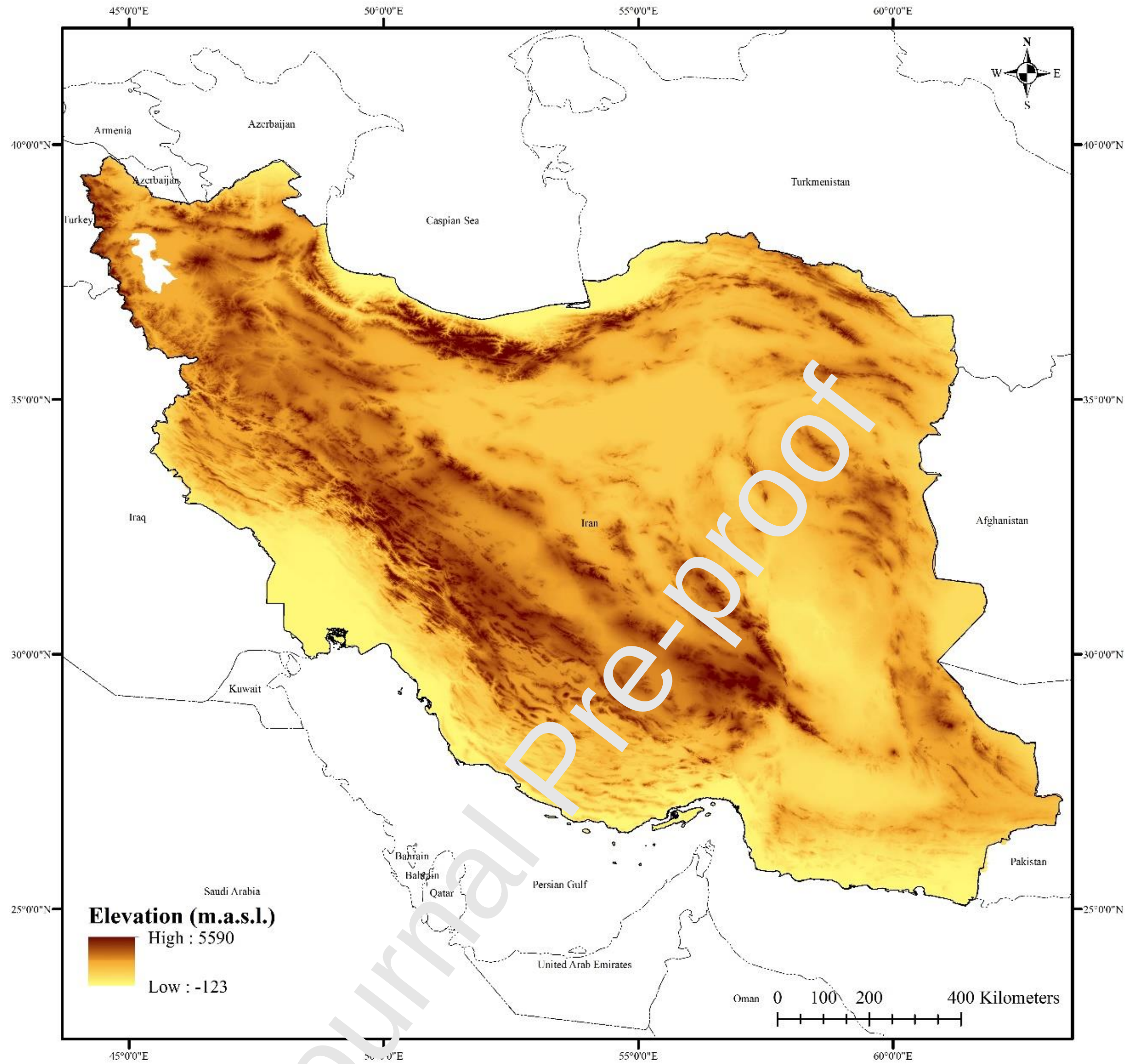


Figure 4: Iran’s geographical location, topography, and it’s neighbor countries

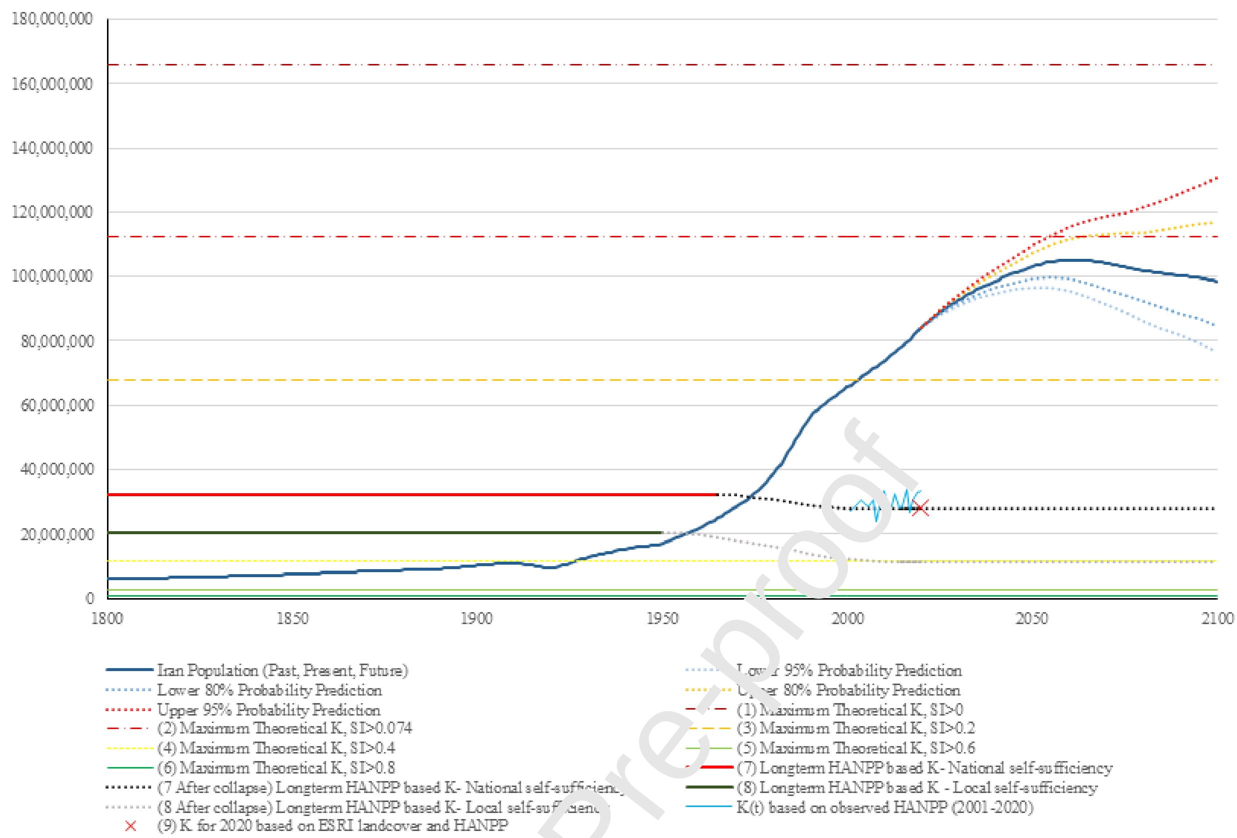


Figure 5: Calculated K value for different scenarios. Long-term HANPP based K, and the values for 2001-2020 shows Overshoot and collapse behavior in Iran's population

Declaration 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.

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

CRediT authorship contribution statement

Mostafa Khorsandi: Data curation, Methodology, Conceptualization, Software, Formal analysis, Investigation, Validation, Visualization, Resources, Writing – original draft, Writing – review & editing.

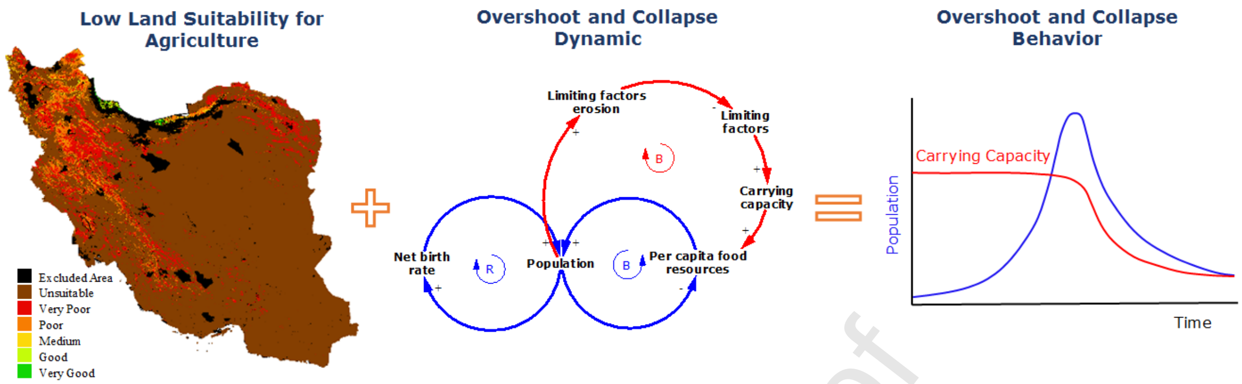
Saeid Homayoni: Supervision, Data curation, Writing – review & editing.

Pieter van Oel: Supervision, Writing – review & editing.

All authors reviewed the paper and contributed to the quality of work.

Journal Pre-proof

Graphical abstract



Highlights

- An Earth observation method was used to assess land suitability for agriculture.
- A HANPP method was developed to estimate food availability.
- An analytical tool was developed to estimate water resources carrying capacity.
- Our study showed Iran's current population is beyond its local carrying capacity.
- Iran appeared to be a case of overshoot and collapse in environmental policy.