Application of the ecological footprint method for measuring sustainability of agricultural land use at a micro level in Barddhaman district, West Bengal, India

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In the present study we used the ecological footprint method to numerically measure the sustainability of agricultural production at the micro level. For this, two community development blocks of Barddhaman district, West Bengal, India were selected. As a consumption-based method, it is most suitable for measuring cropland footprint, biocapacity of croplands, and their ecological surplus and deficit status of an environmental indicator. The integrated result represents higher sustainability of agricultural system, but crop-wise assessment explores some negative aspects with respect to self-sufficiency of the study area that demand necessary transformation of existing cropping pattern.

Keywords: Agricultural land use, biocapacity, ecological footprint, sustainability.

AGRICULTURE is the prime economic activity which is directly related with the supply of food[1]. Rapid growth of the global population is increasing the gap between the demand and supply of food. According to Malthus[2], the increasing world population will aggravate the problem of food scarcity. Increasing use of non-renewable natural resources and non-sustainable use of land are additional problems. By 2050, to feed 2.3 billion more people, the global food demand will need to grow by 70% while unsustainable agricultural production could decrease the ecological carrying capacity of agricultural land[3–6]. Therefore, the assessment of sustainability of agricultural activities should be given priority in research to back sustainable supply of food.

According to Stern[7], consumption is a result of interaction between humans and the environment, and its impacts are biophysical. This has to be also taken into account in the case of food consumption. Therefore, from an environmental point of view sustainable food production systems should be given importance in research.

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In this study, agricultural sustainability has been analysed by quantifying the ecological footprint of croplands to achieve agricultural self-sufficiency at the micro level.

Significance of ecological footprints in resource analysis

The ecological footprint is an indicator based on consumption of natural resources and is one of the most widely used indicators for the sustainability in using biophysical resources. The approach was developed by Wackernagel and Rees[8] as an indicator of environmental sustainability that measures human load on nature by assessing how much biologically productive area is needed to maintain a given population with a given consumption pattern at a given point of time. The ecological footprint method has introduced a new way to the measurement of human impact on the environment by quantifying the effects of food consumption and food supply systems[9]. If the ecological footprint exceeds the available biocapacity, then this indicates a so-called ecological deficit which is an important measurement of the extent to which a population exceeds sustainable limits. The reverse condition indicates 'ecological surplus' suggesting more sustainable state of human habitation.

As a result, physical areas are expressed in so-called global hectares. These measurement units are hectares with world average productivity and the biocapacity of all biologically productive areas on the planet. The advantage of using global hectare is that it makes it easier to compare regions and nations. This approach is useful for measuring the differences between sustainability of two spaces. It uses 'land use' units as these are more familiar, acceptable and closer to life for decision makers than other units[10].

Methodology of ecological footprint

Ecological footprint calculations are based on six assumptions[11]. These are as follows:

(i) The majority of resources people consume and the wastes they generate can be quantified and tracked.
(ii) Resources and wastes can be converted into biologically productive land.
(iii) By weighting method different land types can be converted into a common unit of global hectare.
(iv) Such transformation into global hectare makes it easy to have an integrated indicator of ecological footprint or biocapacity.
(v) Human demand, expressed as the ecological footprint, can be directly compared to nature's supply, biocapacity, when both are expressed in global hectare.
(vi) Area demanded can exceed area supplied, if demand on an ecosystem exceeds its regenerative capacity.

Therefore, the ecological footprint is a consumption-based indicator. It allocates the resource use of production, transportation, distribution and consumption to the place of consumption, to final consumers.

In a footprint analysis, the following steps are considered:

First step: Calculation of the ecological footprint of each consumption item. The computational forms can be defined as

$$A_{\mathrm{i}} = C_i/Y_i,$$

where i is the item type of consumption, Y_i the annual average yield of the item (kg/ha), C_i is per capita consumption of the item (kg/capita) and A_i is the per capita ecological footprint of the item (ha/capita).

Second step: Calculation of the ecological footprint of the research region computed as

$$\mathrm{ef} = \text{sum of } (r_j A_i) \; (j = 1, 2, \ldots, 6),$$

where ef is the per capita ecological footprint of the research region (ha/capita). j is the bioproductive area classified into six types: cropland, forest, pasture, fisheries, built-up land and fossil energy land. r_j are equivalence factors which represent the world's average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas. Cropland, for example, is more productive than pasture, and so has a larger equivalence factor than the latter[12].

The total ecological footprint of a research region can be defined as

$$\mathrm{EF} = N(\mathrm{ef}),$$

where EF is the total ecological footprint (ha) and N is the population of the research region.

Third step: Calculation of the biological capacity of a research region. The total biocapacity of a region is the sum of its bioproductive areas. Per capita biocapacity can be defined as

$$\mathrm{ec} = a_j r_j y_j \; (j = 1, 2, \ldots, 6),$$

where ec is the per capita biocapacity (ha/capita), a_j the per capita bioproductive areas, r_j the equivalence factors and y_j are yield factors that describe productivity of an item in a given country or region relative to world average productivity of that item.

The total biocapacity of research region can be defined as

$$\mathrm{EC} = N(\mathrm{ec}),$$

where EC is the total biocapacity of the research region (ha) and N is the population of the research region.

Fourth step: Calculation of ecological deficit. An ecological surplus indicates a situation when biocapacity of a region exceeds its footprint whereby

Ecological deficit (ha) = footprint (ha) – biocapacity (ha)

Calculation of the equivalence factors

Quantification of the equivalence factors is required to measure different land types in one standard measurement unit. This converts the various land types to the world average productivity[8,13].

The calculation of equivalence factors is based on suitability index of five land categories mentioned in the global agro-ecological zones (GAEZ) model. The equivalence factor is the ratio of the suitability index for a particular land-use type to the average suitability index for all land-use types[11].

Approaches to measure ecological footprint

The ecological footprint is calculated based on the following two approaches:

(i) The first method of calculation called 'compound' footprinting uses a top–down approach. It was developed by Wackernagel and Rees[8], who calculated the ecological footprint based on aggregate data at national and regional level.
(ii) The other method follows a bottom–up approach. It was developed by Simmons *et al.*[14], to be applied at micro spatial scale using individual data.

Ecological footprint and agricultural sustainability

Research questions related to land and resource use can be analysed with the concept of ecological footprint as a

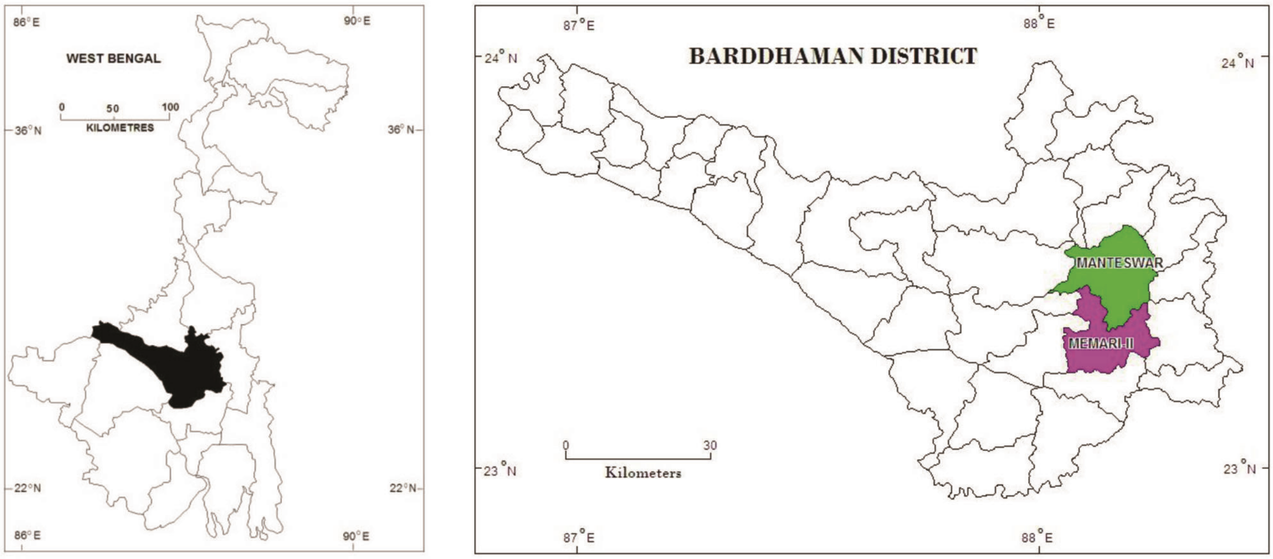

Figure 1. Location of the study area.

biophysical indicator[15,16]. As the indicator compares the environmental impacts of consumption, it defines ecological balance and unsustainable consumption by taking into account the finite nature of natural resources. The ecological footprint therefore suits the strong environmental sustainability approach[17] and it is suitable to measure the level of agricultural sustainability.

Case study: Barddhaman district, West Bengal, India

Barddhaman district (divided into the Purba and Paschim Bardhaman districts in 2017) is known as the 'rice bowl' of West Bengal, India, because of high agricultural production in its eastern part mirroring the effects of a fertile alluvial plain leading to high crop specialization. Two community development (CD) blocks, Manteswar and Memari-II, were selected for the present study. These blocks are located at the eastern part of the district and are agriculturally well developed (Figure 1). The cropping pattern in Manteswar is dominated by paddy and that in Memari-II by both paddy (*Oryza sativa* L.) and potato (*Solanum tuberosum* L.)

Agricultural characteristics of the study area

In 1970, due to a lack of irrigation water in the *rabi* season, fields were used for the cultivation of a single crop. As irrigation utilizing groundwater started to become available to farmers, there was a gradual shift from mono- to multi-cropping systems. Introduction of high-yielding paddy varieties during the late 1980s facilitated a huge shift in the area under this crop. Since then, rice is the dominant crop for both *kharif* and *rabi* season in Manteswar, and more than 93% of the cropped area is occupied by this crop. In Memari-II, rice occupies >60% and potato >30% of the cropped area respectively. Other crops like pulses, oilseeds, vegetables and wheat (*Triticum aestivum* L.) are also cultivated but these are minor. Thus, today's agricultural activities are characterized by a high degree of crop specialization and very little diversification.

Materials and methods

The crops commonly grown by inhabitants of the study area, such as paddy, wheat, pulses, oilseeds, potato and vegetables were selected to calculate their cropland footprint. Data related to productivity of different crops and consumption of food were collected by a primary survey. Manteswar CD Block consists of 13 Gram Panchayats (GPs; administrative units within blocks) and Memari-II CD block consists of 9 GPs. For collection of primary data one village was selected from each GP unit. The farming and non-farming households were the ultimate stage of sampling. A complete list of households in each selected village was prepared with further classification of the households into non-farming, small (below 2 ha), medium (above 2 ha and below 6 ha) and large (6 ha and above) farm households, based on the operational holding. Finally, a sample of 20 farming households from each selected village, almost equally distributed across four size categories, was selected for data collection. Personal interviews using a closed questionnaire were conducted from the farming and non-farming households selecting one member from each having enough knowledge and information about farming activity and consumption of food by the family. Population of 2016

Table 1. Yield factor of Manteswar CD block (2016)

Gram Panchayat	Paddy	Wheat	Pulse	Total oilseed	Potato	Vegetable
Baghasan	1.4833	0.7485	0.68	0.7017	1.7445	1.446541
Susunia	1.4188	0.8233	0.517	0.5614	1.6652	1.509434
Bhagra–Mulgram	1.4188	Nil	0.571	0.6315	1.5859	1.63522
Manteswar	1.4833	0.6362	0.626	0.6035	1.5859	1.761006
Denur	1.2898	0.7934	0.816	0.5754	1.5859	2.201258
Kusumgram	1.3543	0.8158	0.672	0.5894	1.6494	1.949686
Bamunpara	1.4833	Nil	0.819	0.6035	1.6177	1.320755
Putsuri	1.4188	0.8458	0.539	0.5473	1.7604	1.679245
Mamudpur-I	1.3543	Nil	0.541	0.5052	1.5859	1.320755
Mamudpur-II	1.335	Nil	0.781	0.5193	1.5859	1.823899
Jamna	1.4188	0.756	0.694	0.5614	1.6652	1.54717
Piplon	1.4833	0.8308	0.666	0.5894	1.5859	1.509434
Majhergram	1.4123	Nil	0.724	0.6596	1.6018	1.572327

Source: Calculated based on data collected from field survey and FAO[19].

was projected based on the census population data of 1961–2011. Data about area under different crops in 2016 were collected from the Agricultural Development Office in each CD block. Following Li and Li[12], equivalence factor was set to 2.9.

Calculated results of two CD blocks were tested at 95% significance level. As the sample size was <30, 'approximate test' using normal distribution was selected. The results were tested using the formula

$$Z = (p - p_0)/\text{SE of } p,$$

where p and p_0 are the proportion of samples from the population and SE is the standard error of estimate[18].

Calculation of yield factor

The yield factor of different crops was calculated by dividing the average yield of the study area by that of the world for the respective crop.

Results and discussion

Paddy occupies an area of 23,162 ha in Manteswar and 12,516 ha in Memari-II. Yield factors of paddy, potato and vegetables were >1, and of wheat, pulses and oilseed <1 in both the CD blocks (Tables 1 and 2). The productivity of paddy was above world average in both study areas. The area under pulses (including *Lens culinaris* L., *Vigna mungo* L., *Vigna radiate* L. and *Pisum sativum* L.), wheat, oilseeds (including *Brassica juncea* L., *Sesamum indicum* L. and *Helianthus annuus* L.) is less and their lower average productivity cannot meet the demand of the study area. Both the CD blocks are self-sufficient in the production of potato with an average productivity of this crop above the world average; however, the area under potato is larger in Manteswar than in Memari-II. Cropped area under vegetables (include cauliflower, cabbage, onion, tomato, brinjal, french beans, cucurbits) was 2840 and 1890 ha in Manteswar and Memari-II respectively.

Characteristics of cropland footprint

The amount of land required to supply food for the survival of the population living in the study area, was expressed by cropland footprint based on the consumption of crops (Figure 2). In Manteswar CD block Kusumgram, Jamna, Baghason, Susunia and Mamudpur-I showed very high cropland footprint (7000–9000 ha), whereas the rest of the GPs were characterized by a cropland footprint of 4000–7000 ha. On the other hand, in Memari-II CD block Kuchut, Bohar-II and Satgachia-I showed a very high cropland footprint (6400–8800 ha), and the rest of the GPs were characterized by cropland footprint of 3800–6400 ha.

Detailed observation of the cropland footprint will reveal consumption characteristics in the study area. Instead of high productivity per hectare, cropland footprint under paddy is high because it is given the first priority as food crop. Apart from paddy, there are other crops like wheat which have significant potential to be used as a food crop due to which the study area documents cropland footprint under wheat. Instead of less per capita consumption, cropland footprint under pulse and oilseeds is higher due to low productivity per hectare. High productivity of potato has resulted in a lower cropland footprint under the crop.

Characteristics of cropland bio-capacity

Biocapacity depends on the area of cropland and yield factor (Tables 1 and 2). GP-wise distribution of cropland biocapacity represents that in Manteswar CD block, Susunia, Jamna, Majhergram and Baghason had very high cropland biocapacity (10,000–14,000 ha), whereas rest of the GPs had a cropland biocapacity of 4000–10,000 ha.

Table 2. Yield factor of Memari-II CD block (2016)

Gram Panchayat	Paddy	Wheat	Pulse	Total oilseed	Potato	Vegetable
Barpalason-I	1.2898	0.6362	0.6530	0.5614	1.9031	1.5723
Barpalason-II	1.3543	0.6662	0.5440	0.5333	1.8238	1.7610
Bohar-I	1.3221	0.7036	0.5440	0.5333	1.9190	1.5094
Bohar-II	1.2898	0.7410	0.5980	0.5473	1.8714	1.8239
Bijur-I	1.1866	0.7470	0.7890	0.5193	1.8555	1.9497
Bijur-II	1.2318	0.8158	0.6800	0.5586	1.8397	2.0126
Kuchut	1.4510	Nil	0.8700	0.5600	1.9824	1.9433
Satgachia-I	1.2189	Nil	0.5490	0.5319	1.9666	2.1635
Satgachia-II	1.1479	Nil	0.6040	0.5010	1.8555	1.7611

Source: Calculated based on data collected from field survey and FAO[19].

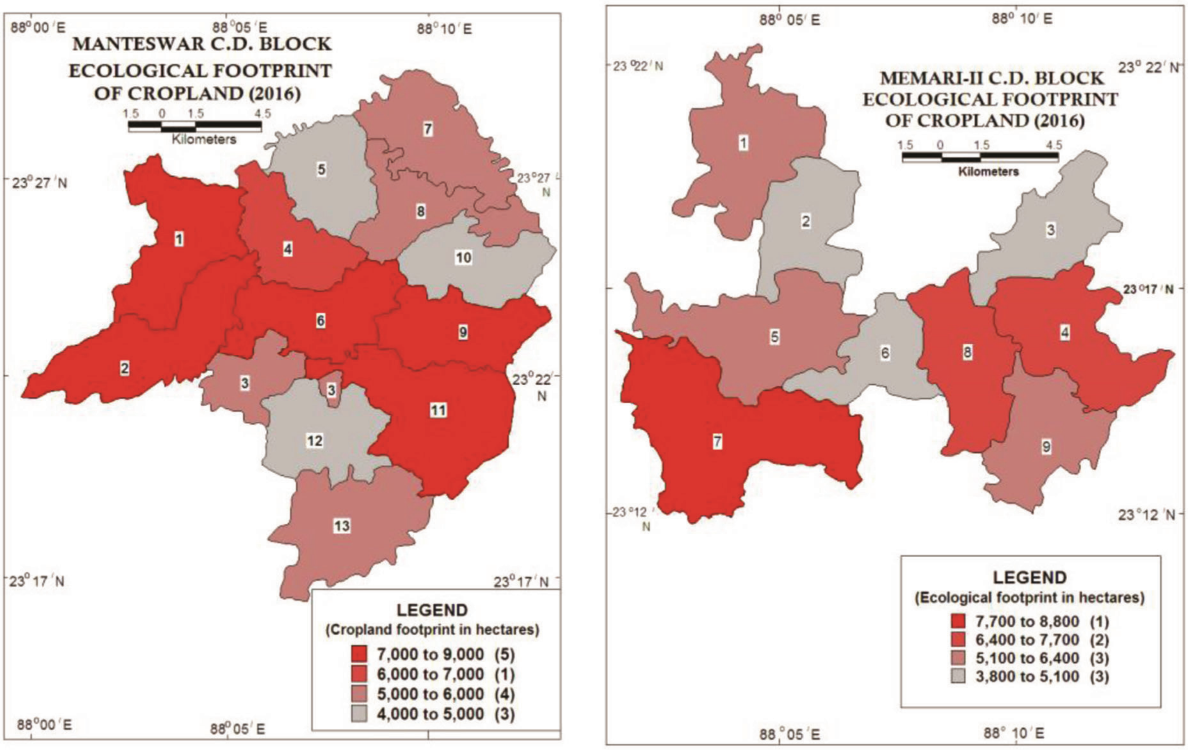

Figure 2. Cropland footprint of the study area, 2016.

On the other hand, in Memari-II, Kuchut, Bohar-II and Bijur-I GP had very high cropland biocapacity (13,000–20,000 ha), while the rest of the GPs had cropland biocapacity of 10,000–13,000 ha.

Some key features characterize the spatial pattern of cropland biocapacity of the study area. In Manteswar CD block, cropland biocapacity under paddy is higher than the other crops due to its large gross cropped area and very high productivity. In both the CD blocks, cultivation of wheat in a few areas with very low productivity is the main cause for the low biocapacity under this crop. For the same reason, biocapacity of pulses and oilseeds is low. The numerical value of cropland biocapacity is higher in Memari-II than that in Manteswar. The main cause is the difference in cropping pattern in the CD blocks. In Manteswar, more than 90% of the gross cropped area is used for rice, whereas nearly 37% of the gross cropped area is occupied by potato in Memari-II. Due to sandy loam soil, yield of potato is very high here, which has resulted in a high yield factor of this crop. Thus this crop has higher potentiality to increase the biocapacity of the cropland. So, there is a direct relationship between crop diversification and cropland biocapacity.

Ecological status of cropland

The areal value of cropland footprint with respect to cropland biocapacity is expressed as the ecological status of the cropland. The value of the cropland biocapacity is

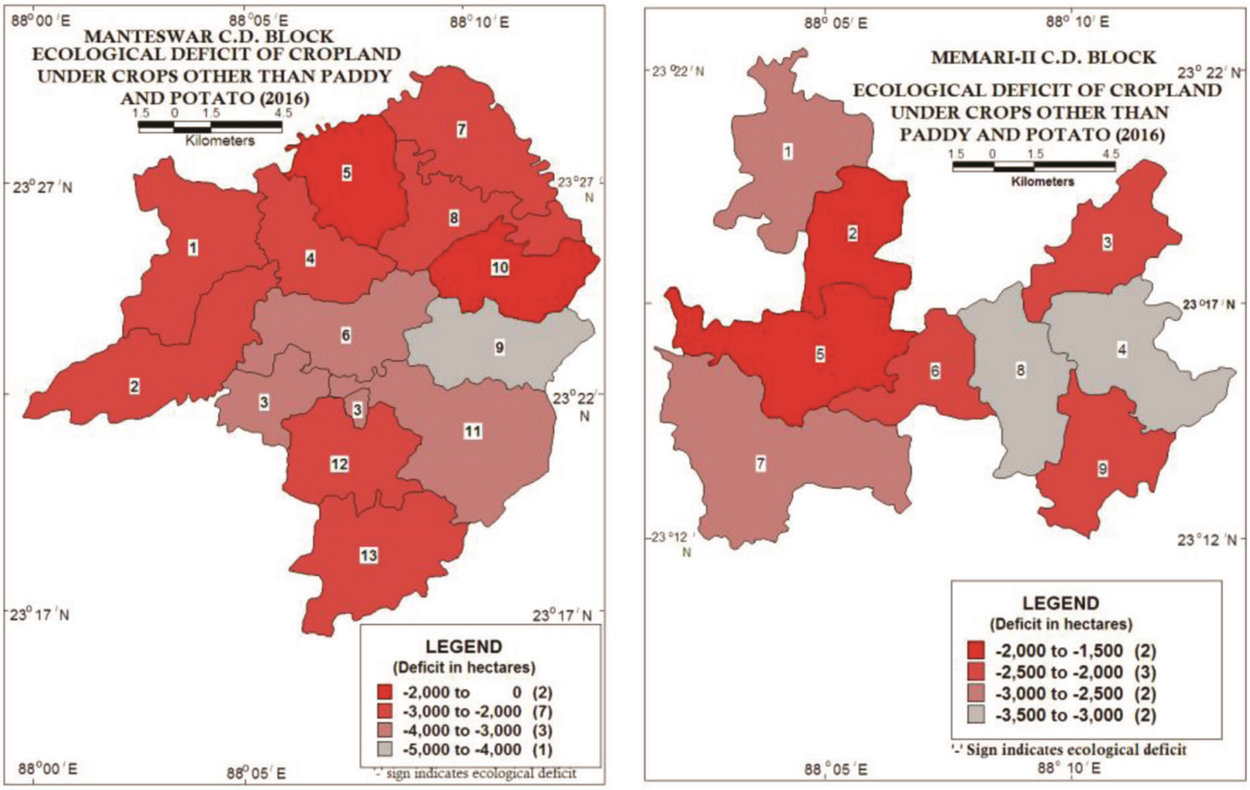

Figure 3. Cropland deficit under pulses, oilseeds, wheat and vegetables, 2016.

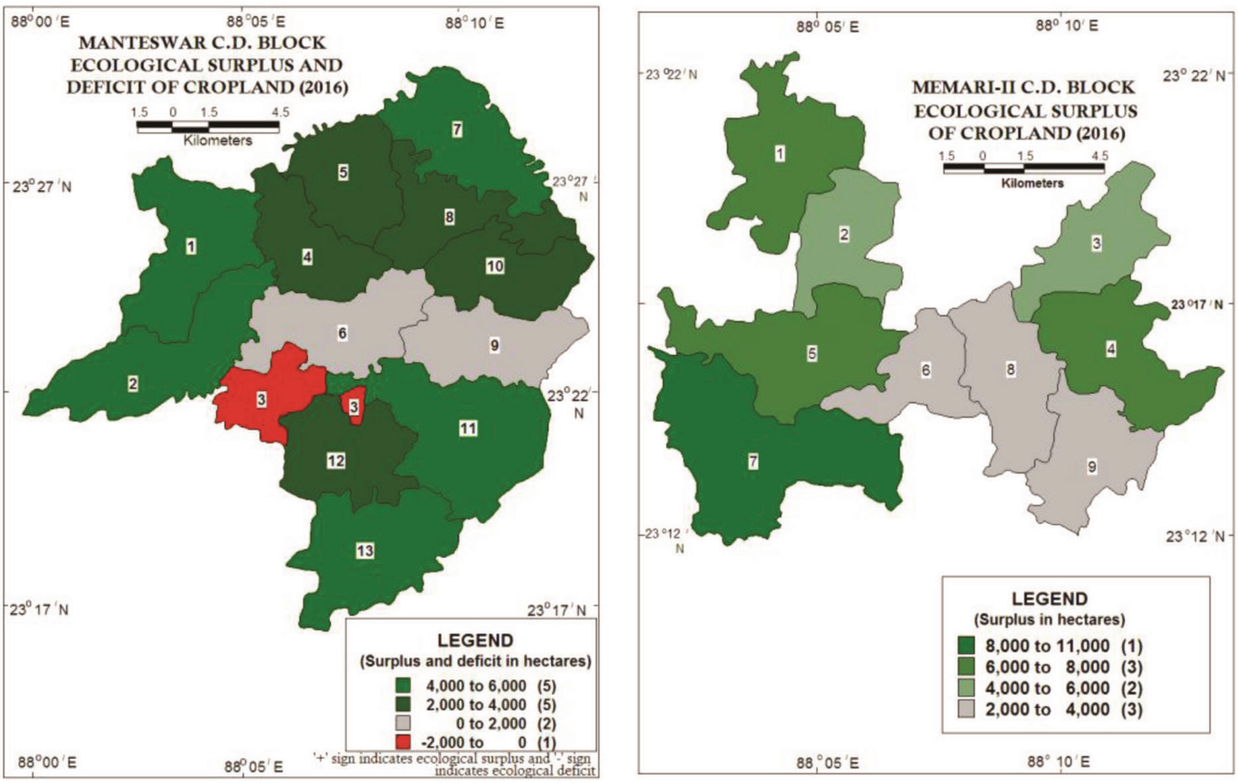

Figure 4. Intergated ecological status cropland in the study area, 2016.

Table 3. Comparison between two CD blocks

Particulars	Manteswar Mean	Manteswar Standard deviation	Memari-II Mean	Memari-II Standard deviation	Calculated |Z| value	Tabulated |Z| value	Remarks
Cropland footprint	6128.84	1479.03	5938.85	1505.20	0.29	1.645 at 95% significance level	No difference
Cropland biocapacity	9249.48	2541.99	11654.24	3708.57	1.69		More in Memari-II
Surplus and deficit of crops	3120.64	2034.48	5715.38	2656.66	2.47		More in Memari-II
Surplus under paddy	5634.98	1833.89	3428.89	1930.74	2.69		More in Manteswar
Surplus under potato	190.65	82.38	4768.79	1186.23	11.56		More in Memari-II
Crops other than paddy and potato	–2704.99	1057.6	–2482.30	639.20	0.61		No difference

greater than the cropland footprint, which indicates an ecological surplus of cropland. A value of the cropland biocapacity lower than the cropland footprint indicates an ecological deficit of cropland. Crop-wise assessment of ecological status reveals that both the CD blocks experience an ecological surplus of cropland under paddy amounting to 73,255 ha and to 30,860 ha in Manteswar and Memari-II respectively. Very high yield resulting from highly fertile soils and high-yielding varieties has caused such surplus. Relatively more area under paddy in Manteswar than in Memari-II is the main cause of surplus in the former compared with the latter.

Due to higher specialization of paddy in Manteswar CD block, the GP has more cropland surplus under paddy compared to Memari-II. However, the reverse situation can be found for potato. Dominance of sandy loamy soil, higher yield of potato, large area under this crop, and cultivation of this crop on commercial basis result in higher ecological surplus of patato in Memari-II compared with Manteswar, where it is cultivated only to meet the domestic demand. Beside this, dominance of clay soil in Manteswar does not allow profitable cultivation of the crop.

Ecological status of crops other than paddy and potato shows significant amount of ecological deficit in both the blocks (Figure 3). Lack of crop diversification and very low productivity of pulses, oilseeds, wheat and vegetables cause such deficit. The deficit is 35,165 and 24,163 ha in Manteswar and Memari-II respectively.

The integrated ecological status of all crops represents a more satisfactory situation (Figure 4). In Manteswar all GPs, except Bhagra–Mulgram have ecological surplus of cropland (2000–6000 ha). Bhagra–Mulgram is located in a flood-prone area; crop productivity during rainy season was adversely affected due to floods in 2015. This is the main factor for the GP to have cropland deficit. In Memari-II all the GPs experience ecological surplus of cropland. Here the value of surplus is higher (2000–11,000 ha) compared with Manteswar. Paddy and potato-dominated cropping pattern in Memari-II has made it more diversified than Manteswar, where it is dominated by paddy only. Hence, crop diversification is a significant controlling factor to increase cropland biocapacity and hence, cropland surplus.

Inter-block comparison has been carried out with the help of 'Z' test. Let us consider the null hypothesis that there is no significant difference in terms of every calculated variable between Manteswar and Memari-II. Table 3 shows results of the test.

The results represent absence of significant difference between Manteswar and Memari-II in terms of per capita consumption of crops. Therefore, characteristics of cropland footprint of the blocks are identical but difference in cropland biocapacity contributes to surplus of cropland in Memari-II than in Manteswar. Nature of cropping pattern and degree of crop diversification have the potential to increase cropland biocapacity and cropland surplus. Agricultural specialization on food crops decreases cropland biocapacity, while specialization on cash crops increases cropland biocapacity. More gross cropped area under potato in Memari-II helps increase its cropland biocapacity compared to Manteswar. Both the CD blocks are not self-sufficient in crops like wheat, pulses and oilseeds, and vegetables.

Conclusion

Effectiveness of ecological footprint method for analysis of agricultural sustainability with constant or decreasing availability of croplands of biophysical environment is presented here. It is clear that this method helps identify the anomalies of agricultural production relative to population–demand of food. Most importantly, linking the outcome of crop-wise analysis with population demand explores the unequal pace of land utilization and cropping pattern that demand changes in decision-making prospect for agricultural management.

Cropland footprint is mainly controlled by the consumption pattern of people in the study area while geographical environment, productivity of land, occurrence of natural calamities and selection of crops in the cropping pattern play a dominant role to determine cropland biocapacity and ecological surplus of croplands. The study area is self-sufficient in terms of cropland under paddy and potato, but depends on other areas to meet cropland deficits of pulses, vegetables, wheat and oilseeds. Diversification of cropping pattern helps increase cropland surplus and hence, agricultural sustainability. Cash crops like potato have higher potentiality to increase cropland surplus compared to food crops like paddy.

However, the integrated result of all crops indicates higher sustainability of the agricultural system, but crop-wise assessment explores some negative aspects with respect to self-sufficiency of the study area. Thus well designed and consumption-based agricultural solution with more emphasis on ecologically deficit crops is required to improve agricultural sustainability and self-sufficiency.

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