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Research article

Identification, management and pecuniary impact of major carbon footprint contributor in potato production system of north-west India

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A R T I C L E I N F O

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A B S T R A C T

Assessment of carbon footprint of a crop is an important component of sustainable crop production, as it helps in framing effectual and viable crop management strategies to minimize ecosystem tampering. Thus, in present investigation carbon footprint of potato production system in different agro-climatic zones viz. undulating plain zone, central plain zone and western plain zone of North-west India were estimated, and compared with the recommended practices of these zones. The carbon footprint was higher in undulating plain zone followed by central plain zone and western plain zone with values being 343, 296 and 220 kg CO_2 eq./t tuber yield (TY), sequentially, whereas same were 198 kg CO_2 eq./t tuber yield (TY) in case of recommended practices. The social cost of carbon (SCC), that represents economic damage from the CO_2 emissions, was also estimated. The integrated net economic balance (net return from yield – SCC) was also better in case of recommended practices. The major sources of emission from potato production system were fertilizer (NPK) application (42 %), irrigation (20 %), seed (14 %), fertilizer production (13 %) and energy use (excluding Irrigation) (5 %). Top most in the list of carbon footprint contributors was fertilizer application which was due to imbalanced application of these, and for getting the clear picture of this imbalance as well as its impact, a new and exclusive index- Relative Imbalance Fertilization Index ($RIFI_{cf}$) was developed and tested. Carbon footprints were also related to tuber yield and an empirical model was developed that can be used to predict tuber yield on the basis of carbon footprint of potato production system. An increase in tuber yield with increasing carbon footprint was noticed, which became somewhat static at higher emissions. The findings of this investigation provide a clear picture of quantitative GHG emissions due to imbalanced inputs that can be plummeted to some extent if already existing recommendations are followed.

1. Introduction

As per UN projections, world's population is likely to increase from 7.8 billion in 2020 to 9.7 billion in 2050 [[1,2]]. In India it is

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expected to reach 1.7 billion by that time. It will be a challenging task to feed this ever-growing population. India will have to feed 430 million additional mouths by 2050 [3] and food insecurity is anticipated as the biggest threat that India will face by that time. The potato crop can solve this problem of food insecurity/shortage due to demand for food by growing population as FAO has already recommended potato as a food security crop of future and placed it in the upper stratum of recommended food security crops. Being a food security crop of future, there is a need to increase its productivity and for doing so the general practice, especially in developing countries, is to alter or increase the inputs which most often results in environmental deterioration [4] due to increased carbon footprint in the atmosphere, from within as well outside of the farm gate.

Potato is and will be an integral part of world's food system, which is responsible for more than one-third of global anthropogenic greenhouse gases (GHG) emissions [5]. Potato production requires relatively higher inputs such as fertilizers, seed, plant protection agent's, and energy/fuel for mechanical operations [6], which leads to enhanced emission of GHGs. Carbon footprint is one of the noble term coined for such emissions associated with the produce [7]. Carbon footprint include all the emissions from production activities (pre-farm, on-farm and post-farm) and hence are useful in pursuing more effective climate change policies for a production system. Only after knowing about the carbon footprint, the effective mitigation options for reducing these footprints can be designed and implemented. These mitigation options can either be resource conservation practices like carbon sequestration [4], reduction in soil organic carbon (SOC) depletion [8], nutrient management practices, building soil health and quality [9], or energy conservation techniques like sustainable mechanization [10], reduced use of unnecessary farm machinery etc. Moreover, already existed/demonstrated technologies and recommendations, if followed, can also reduce a significant amount of emissions [4]. This reduction in emissions can go up to 85 % with already demonstrated technologies as is reported for Europe [11].

In India, potato is cultivated in an area of 2.15 million ha with a total production of 48.52 million tonnes having an average productivity of 22.56 t ha^{-1} [12] and North-West India contribute significantly to this, in terms of area as well as production. To meet food requirement of growing population of India no doubt, there is a need to increase potato production in the country. At the same time this should not temper our environment, especially through GHG emissions [13], which results due to excessive or imbalanced use of resources for getting higher yields [[14,15]]. So, there is a dire need to identify major carbon footprint contributor of potato production system so that the mitigation options to counter/manage such major contributors be explored, designed and applied. Moreover, our earlier studies have also revealed that the inappropriate or imbalanced input of resources like fertilizers (in comparison to recommended), has resulted in relatively more emissions [14] which in turn increases social cost of carbon (SCC)-an index to represent expected economic damage from CO_2 emissions. It is pertinent to mention here that neither a detailed carbon footprint study, its social cost and emission comparisons (between farmers and recommended practices) of potato production system in North-West India have been attempted nor an effort to develop an index [9] to reveal carbon footprint related imbalanced inputs in the region have been made.

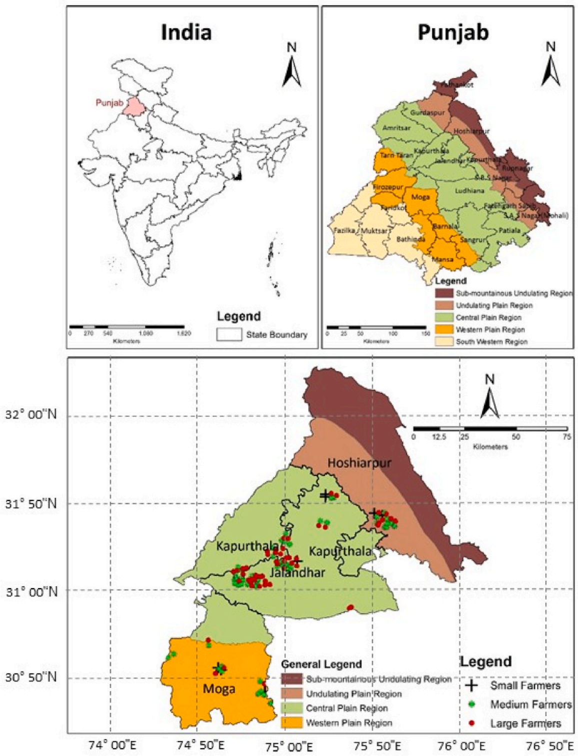

Fig. 1. Study area representing potato growing agro-climatic zones of North-West India.

Keeping in view the aforementioned facts and importance of revealing carbon footprint of potato production system, the present study was formulated and initiated in potato growing areas of north-west India. The study is based on the hypotheses that carbon footprints from potato production system can be reduced significantly if recommended practices for the region are followed. The carbon footprint of potato production system along with social cost of carbon due to these emissions was estimated and compared with that of recommended practices. The overall aim of our investigation was to estimate the GHG emissions, in the form of carbon footprint, associated to the production of potato, its comparison with recommended practice in terms of returns, and to develop an index that can evaluate the extent of carbon footprint due to imbalanced inputs, especially fertilizers. Such information can be used to suggest potential management strategies for mitigation of GHGs emission.

2. Materials and methods

2.1. Description of the study area

The present investigation was conducted in three major potato growing agro climatic zones viz. Undulating plain zone (R–I); Central plain zone (R–II) and Western plain zone (R–III), of North-West India (Fig. 1) [16] during the years 2018-19 to 2020-21. Undulating plain zone is humid to sub-humid with an annual average precipitation of 900 mm, Central plain zone is semi-arid to dry sub-humid with mean precipitation of 561 mm and Western plain zone is arid to extremely arid with 360 mm precipitation. The study area extends from $30^{0}48'$-$32^{0}08'$N latitude to $74^{0}90'$-$7^{0}34'$E longitude. The total area covered for present study was around 10, 000 km^2. The average monthly income of farmers of the area under study is Rs. 16,349/- per agricultural household which is the highest in the country.

Potato is a major cash crop of the region and plays an important role in meeting out the requirement of potato in the country. Climate of the study area varies from humid and sub-humid to semi-arid and arid and is generally dry except during monsoon [17]. Soils of the study areas are light in texture and classified as loam.

2.2. Selection of farmers and data collection

For carrying out present investigation, an exhaustive survey was conducted to collect and authenticate the information required. All the required information, from land preparation to transportation of harvested crop was collected in a systematic manner (Fig. 2) as per the pre-defined questionnaire prepared for the purpose and as per the cool farm tool (CFT) requirement [18]. Quantitative questionnaire was used to collect data related to use of various inputs like seed, diesel fuel, fertilizers, biocides (herbicide, insecticides & fungicides), number and source of irrigation. Information on tuber yield (TY) of each farm was also recorded. Thus, the present analysis included practices, machinery and energy carriers used during potato cultivation (Fig. 2). One hundred and eighteen, small, medium and large farmers, were selected representing whole of the study area (Table 1). Only farmers with a minimum of 10 years or

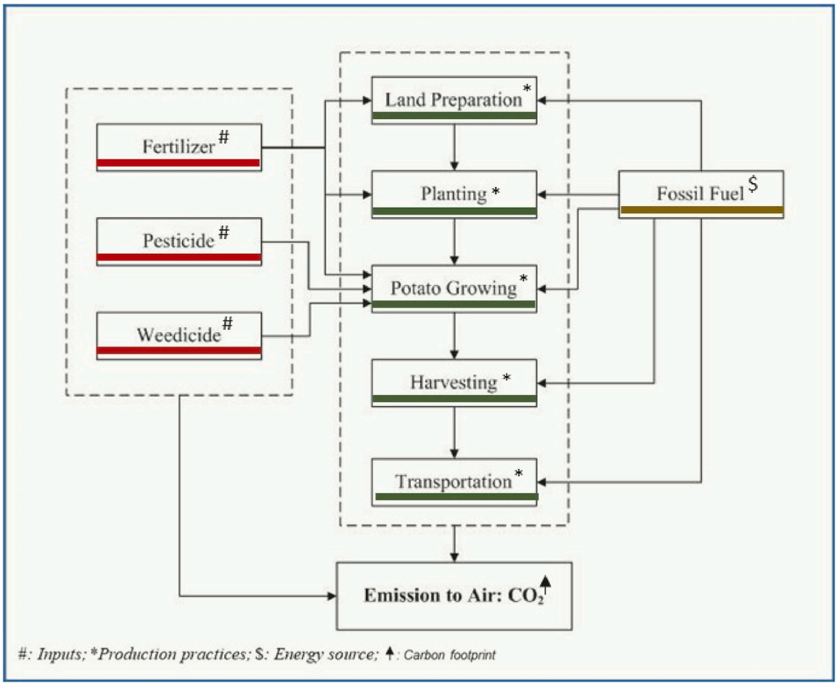

Fig. 2. Potato production system boundary used in the carbon footprints assessment.

more of experience in potato cultivation were interviewed by one-to-one interaction.

2.3. Physico-chemical properties of soils under the study

Soil samples were also collected from the potato fields of the surveyed farmers and were analysed for various physico-chemical properties (Annexure A) as per the standard procedures. Soil pH of sampled field ranged from 6.5 to 8.4. Organic carbon content also showed a huge variation in the soil i.e., low to medium ranging from 0.17 to 0.77 per cent irrespective of zones and class of farmers. All the soils of different zones, in all the three farmer classes, were having low average available nitrogen (ranged between 130 and 223 kg ha^{-1}). Average available phosphorus in all the class of farmers in zones R–I & R–III was in medium range (ranged between 12 and 18 kg ha^{-1}) except R–II (ranged between 24 and 25 kg ha^{-1}), where it was found to be high. A very low variation in average available potassium, which was in medium range, was observed in R–I & R–II (ranged between 239 and 276 kg ha^{-1}), whereas its low level was noticed in R–III (ranged between 116 and 129 kg ha^{-1}) in all three classes of farmers. Micronutrients (Zn, Fe, Cu, and Mn) have also shown lesser variation in average contents; however, these were found to be higher than critical limits in all the soils.

Imbalanced fertilization Index, Social Cost of Carbon and net Economic Balance:

Relative Imbalanced fertilization index was evaluated using the empirical model developed during the present investigation. Social cost of carbon (SCC)was calculated as per the estimated values (for India) given by Ref. [19] using the formula.

SCC═CO_2 emitted x Estimated social cost of carbon emission.

Net economic balance was calculated by subtracting the input cost and social cost of carbon from gross return.

Net Economic Balance = Gross return – (Input cost + SCC)

2.4. Calculation of carbon footprints & statistical analysis

The calculation of carbon footprint was done by open access excel-based mathematical model Cool Farm Tool v.2- beta 3 (CFT). The CFT model was run separately for each data set obtained from the individual farmer through research questionnaire (118 valid questionnaire). Details of important input parameters collected and used to assess the carbon footprints are summarized in Annexure B. The process of harmonization of data, calibration and validation as required by international standards is adopted for the model. MS-Excel program was used to compute descriptive analysis and one-way ANOVA. STATA-16 program was used to estimate the correlation coefficient, regression analysis and significance difference using Kruskal Wallis test.

3. Results

3.1. Production practices and resource inputs responsible for carbon footprints

An apparent variation in input use due to diverse production practices was observed in different potato producing agroclimatic zones of North-West India and recommended practices for the region. The maximum seed rate was used by the farmers of agro-climatic zone R–II followed by R–III and then R–I, but was higher than the seed rate recommended for the region (Annexure B). However, no significant variation on account of seed rate used among the class of farmers was observed. All the farmers were using seed treatment practice prior to planting. Land preparation, intercultural operations, spraying and other field practices were carried out by tractor (diesel operated) drawn implements. In the reference trial, which is based on recommendations (240:100:150 N:P_2O_5: K_2O), no Mulcher was used but farmers of RII and RIII zones used the Mulcher once. Average underground water pumping depth in all the regions was more than the reference trial. Generally, 5 irrigations were applied by farmers of R–II and R–III, whereas only 4 irrigations were applied by farmers of R–I, irrespective of class of farmers, whereas the crop was irrigated six times in reference trials. Mean

Table 1
Carbon footprints (kg CO_2 eq./t (TY) potato) for potato production among in different agroclimatic zones and class of farmers in in North-West India.

Factors/Sources	Undulating plain zone (R–I)				Central plain zone (R–II)				Western plain zone (R–III)				RFT
	C–I	C-II	C-III	Mean	C–I	C-II	C-III	Mean	C–I	C-II	C-III	Mean	
Seed	56^a	60^a	50^a	55 (16.0)	50^a	38^a	37^a	42 (14.2)	25^a	21^{ab}	18^b	21 (9.5)	16 (8.1)
Residue	8^a	8^a	8^a	8 (2.3)	7^a	6^a	6^a	6 (2.0)	6^a	5^b	5^b	5 (2.3)	6 (3.0)
Fertilizer (NPK) production	51^a	42^b	40^b	44 (12.8)	47^a	35^b	36^b	39 (13.2)	33^a	30^a	27^a	30 (13.6)	25 (12.6)
Fertilizers (NPK) application	151^a	133^a	135^a	140 (40.8)	150^a	113^b	114^b	126 (42.6)	103^a	101^a	91^a	98 (44.5)	94 (47.5)
Crop protection	6^a	6^a	5^a	6 (1.8)	6^a	5^a	5^a	5 (1.7)	4^a	4^a	4^a	4 (1.8)	4 (2.0)
Irrigation	63^a	70^a	64^a	65 (19.0)	64^a	53^a	55^a	57 (19.2)	48^a	46^a	42^a	45 (20.5)	42 (21.2)
[a]Energy use	18^a	18^a	17^a	18 (5.3)	13^a	14^a	14^a	14 (4.7)	13^a	11^b	11^b	12 (5.5)	7 (3.6)
Transport	7^a	7^a	7^a	7 (2.0)	7^a	7^a	7^a	7 (2.4)	5^a	4^a	5^a	5 (2.3)	4 (2.0)
Total	**360**	**344**	**326**	**343 (100)^A**	**344**	**271**	**274**	**296 (100)^B**	**237**	**222**	**203**	**220 (100)^C**	**198 (100)^D**

[a] Excluding Irrigation; ^{abc}Values (in rows) lacking a common letter differ ($p < 0.05$); ^{ABC}Values (Total Mean Row) lacking a common letter differ ($p < 0.05$); Values in parenthesis () is % of total carbon footprint of that zone; RFT is Reference trial based on recommended practices.

application rate of nitrogen was relatively less in all the three zones than the recommended practice whereas the same was more in case of phosphorus in these zones (Annexure B). Medium and large farmers of RII and RIII generally apply one extra spray of fungicide in comparison to recommended practice. In case of insecticide except in RI, in both the other zones it was being sprayed as per recommendation.

3.2. Carbon footprints of potato production system of north-west India

A significant variation in carbon footprint from potato production system with in the three agro-climatic zones of North-West India was observed (Table 1). Quantitatively more additive average carbon footprints were observed from the said system in undulating plain zone (R–I) followed by central Plain zone (R–II) and western plain zone (R–III) with values being 343, 296 and 220 kg CO_2 eq./t (TY), sequentially. All these values were significantly higher than the carbon footprint value of recommended practices/reference trial (RFT) (198 kg CO_2 eq./t (TY)). It was further observed that contribution from the factors aiding to these emissions varied markedly with in the agro-climatic zones. The major contributor in all the three zones was fertilizer application as it was responsible for emitting 140, 126 and 98 kg CO_2 eq./t (TY) carbon footprint in R–I, R–II and R–III, respectively. Again these values were higher than that of RFT (94 kg CO_2 eq./t (TY)). Irrigation was observed to be second in the list of factors contributing to these emissions with varying values for all the three zones (65, 57 and 45 kg CO_2 eq./t (TY) for R–I, R–II and R–III, respectively) whereas the same was relatively lower (42 kg CO_2 eq./t (TY)) in RFT. Seed and fertilizer production stood at third and fourth position in this list of factors. Seed was responsible for emitting 55, 42 and 21 kg CO_2 eq./t(TY) and fertilizer production was responsible for emitting 44, 39 and 30 kg CO_2 eq./t(TY)in zones R–I, R–II and R–III, respectively. These values in RFT were 16 and 25 kg CO_2 eq./t (TY) for aforesaid former and later sources. Energy use (excluding irrigation) exhibited relatively less emissions with values being 18, 14, 12 and 7 kg CO_2 eq./t(TY) for R–I, R–II, R–III and RFT respectively. Residue, transportation and crop protection were amongst the last three factors, with relatively lower values, contributing to the carbon footprints in the studied agro-climatic zones as well in RFT.

In order to reveal if there exists a variation in carbon footprint emissions, in various categories of farmers viz. small (C–I), medium (C-II) and large farmers (C-III), with in the three agroclimatic zones the emission data was trifurcated and then studied. In farmer class C–I and C-II and C-III categories and in agro-climatic zones R–I and R–II no significant variation in amount of emissions was observed. In R–III, a variation in emissions from factors- 'seed', 'residue' and 'energy use' was noticed with in the categories of farmers. In case of seed as a factor, significantly higher carbon footprint was noticed from potato production system of C–I category farmers (25 kg CO_2 eq./t(TY)) in comparison to C-III (18 kg CO_2 eq./t(TY)) category in zone R–II of the region. In residue and energy use the contribution from production system of category C–I farmers for residue (6 kg CO_2 eq./t(TY) and energy use (13 kg CO_2 eq./t(TY)) was significantly more than other two categories i.e. C-II and C-III in the afore said zone.

Per cent contribution of GHG's emission from different sources to carbon footprints of potato production is depicted in Table 1**.** The primary sources contributing to the greenhouse gas emissions were fertilizer application (44 %), irrigation energy (20 %), seed (14 %), fertilizer production (13 %) and diesel (5 %) while, other sources *i.e.* pesticides, residue incorporation and transport made meagre contribution (2 %) each.

Seeing significant contribution of fertilization (42 %) towards carbon footprint, the relationship and dependency of carbon footprint on macronutrients applied was determined (Table 2). Carbon footprint had significant and positive correlation with applied nitrogen (r = 0.81**), phosphorus (r = 0.57**) and potassium (r = 0.37**). Further for revealing the influence of applied macro nutrients, simple multiple regression analysis was performed. The regression analysis showed that application of nitrogen and phosphorus had significant influence on carbon footprints. All the three macronutrients accounted for 71 % variation in carbon footprints. It was further observed that application of potassium didn't had a significant influence on carbon footprint. The relationship can be explained by following equation:

$$\text{Carbon footprints (kg } CO_2 \text{ eq./ha)} = 1727.48 + 17.44{*}N + 8.67{*}P + 0.12{*}K, \ (R^2 = 0.71)$$

Where N, P, K = applied nitrogen, phosphorus, potassium, respectively.

3.3. Relative Imbalance Fertilization Index ($RIFI_{cf}$) and its relationship with carbon footprint

During the present investigation it was observed that biggest contributor towards carbon footprint, among the inputs, is fertilizer application. Further when we compared carbon footprint (related to fertilizer application) of farmers practice and recommended practice a noticeable difference in these emissions was observed. It was hypothesised that this difference was because of the imbalance in amount of macronutrient fertilizer applied. So to get a clear picture of this difference an attempt to develop and evaluate a new index

Table 2
Correlation coefficient between carbon footprints and fertilizers NPK application.

	N application (kg/ha)	P application (kg/ha)	K application (kg/ha)
P application (kg/ha)	0.45[a]		
K application (kg/ha)	0.46[a]	0.19[b]	
Carbon footprints (kg CO_2 eq./ha)	0.81[a]	0.57[a]	0.37[a]

[a] $p < 0.01$.
[b] $p < 0.05$.

i.e. Relative Imbalance Fertilization Index ($RIFI_{cf}$) was made. To illustrate the integrated effect of all the three macronutrients into a single number, this new index was developed for potato growing areas of north-west India. In order to develop and evaluate the said index, indicator parameters i.e macronutrients applied were assigned weights as per the coefficient of correlation (r) values (irrespective of +ve or –ve correlation) obtained after correlating the indicator parameters with carbon footprint of potato production system of north west India [20]. Applied macronutrient variation (AMV) (kg/ha) from recommended was used for classifying extent of imbalance fertilization. The AMV was calculated as per following formula

AMV (kg/ha) = Recommended amount (kg/ha) – Applied amount (kg/ha)

(Recommended amount for $N:P_2O_5:K_2O$ is 240:100:150)

The AMV i.e imbalance in macronutrient application was further divided into five categories: Class I (Least imbalance/AMV), Class II (Low imbalance/AMV), Class III (Moderate Imbalance/AMV), Class IV (High imbalance/AMV) and Class V (Extremely high imbalance/AMV) (Table 3). Marks 1.0, 2.0, 3.0, 4.0 and 5.0 were allotted to the classes as per extent of AMV/Imbalance. The classification of classes was done after examining and analysing the extent of carbon footprint associated with amount of macronutrient applied. Finally, the $RIFI_{cf}$ was calculated using the following empirical equation developed during the present investigation

$$\text{Relative Imbalance Fertilization Index } (RIFI_{cf}) = \left(\sum_{i=1}^{n} W_i \, M_c \Big/ \sum_{i=1}^{n} W_i \, M_{mc} \right) * 100$$

Where $_{Cf}$: Associated with carbon footprint; W_i is weight of indicator parameter; M_c is marks of the class in which value of AMV falls; M_{mc}: Maximum marks of the class; i = indicator parameter; n = number of indicator parameters.

$RIFI_{cf}$ of all the three categories of farmers of all the three zones was evaluated (Table 4). It was observed that the value of $RIFI_{cf}$ in undulating plain zone (R–I) was higher than other two zones in all the three categories of farmers with value of $RIFI_{cf}$ being 84.2, 85.0 and 89.2 for small, medium and large farmers, respectively. These values were 34 and 29 % less in case of small farmers of Central plain zone (R–II) and Western plain zone (R–III), respectively. The $RIFI_{cf}$ values were 30 % less in both RII and RIII zones in case of medium farmers. The same were comparatively 33 and 38 % less, when compared with RI, in large category farmers of zones RII and RIII.

3.4. Total carbon footprint and yield

For knowing about the carbon footprint of potato production system more clearly, total carbon footprint per hectare was estimated. Fig. 3 demonstrates the Source based cumulative carbon footprint per hectare and corresponding tuber yield in different agroclimatic zones of North-West India. A clear cut variation in total carbon footprint per hectare among different agro climatic zones and RFT/recommended practice was observed. The data exhibits that the maximum carbon footprint (7751 kg CO_2 eq./ha) was recorded in R–III followed by R–II (7186 kg CO_2 eq./ha), and RFT (6855 kg CO_2 eq./ha) while, minimum was recorded in R–I (5824 kg CO_2 eq./ha).

Along with variation in carbon footprint, a variation in tuber yield amongst the three different agro-climatic zones and RFT was also observed (Fig. 3). Average tuber yield was highest in zone R–III (35.10 t/ha) and was at par with RFT (34.94 t/ha). Zone R–II had an average yield of 26.93 t/ha. The least yield of 16.91 t/ha was noticed in R–I. Further, in order to understand the association between carbon footprint and the tuber yield, trend line analysis was done (Fig. 4). A polynomial relationship between the two revealed that with increase in tuber yield the carbon footprint also increased. This increase was sharp in the beginning and slowed down at higher yields (Fig. 4).

3.5. Social cost of carbon due to carbon footprint and net economic balance

In order to reveal the expected economic damages due to carbon footprints, social cost of carbon was estimated (Fig. 5). Social cost of carbon means the cost related to climate change (+ve or –ve) that results from the additional amount of CO_2 emitted. As per [19], estimated social cost of carbon emission (a commonly employed metric of the expected economic damages from CO_2 emissions) for India is US $ 86 per ton of CO_2 emitted. In present investigation we assumed the emissions from potato production system of north-west

Table 3
Indicator parameters, their weights, different classes representing extent of imbalance and their marks for evaluating Relative Imbalance Fertilization Index ($RIFI_{cf}$) in potato growing soils of north-west Himalayas.

Indicator parameter	Weight	[a]Applied macronutrient variation (AMV)/Imbalance (kg/ha) from recommended				
		<10	10–30	30–50	50–75	>75
		Class I (Least)	Class II (Low)	Class III (Moderate	Class IV (High)	Class V (Extremely high)
Applied N	4.6					
Applied P	3.3					
Applied K	2.1					
Marks		**1.0**	**2.0**	**3.0**	**4.0**	**5.0**

[a] Irrespective of –ve or + ve variation; Recommended dose of macronutrients ($N:P_2O_5:K_2O$ is 240:100:150); 10 is to be taken in class II, Similarly 30 in Class III, 50 in Class IV and 75 in Class V.

Table 4
Relative Imbalance Fertilization Index ($RIFI_{cf}$) values and Variation in carbon footprint (kg CO_2 eq./t (TY) of Potato) from carbon footprint of recommended fertilizer practice in different potato growing agro-climatic zones of north-west Himalayas.

Category	Macro nutrient applied (kg/ha)			AMV (kg/ha) & Class			$RIFI_{cf}$
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	
Small farmers							
RI	171	172	75	−69 (IV)	72 (IV)	−75 (V)	84.2
RII	230	192	150	−10 (II)	92 (V)	0 (I)	55.6
RIII	265	192	163	25 (II)	92 (V)	13 (II)	59.8
Medium farmers							
RI	156	161	113	−84 (V)	61 (IV)	−37 (III)	85.0
RII	216	181	136	−24 (II)	81 (V)	−14 (II)	59.8
RIII	252	188	136	12 (II)	88 (V)	−14 (II)	59.8
Large farmers							
RI	165	156	96	−75 (V)	56 (IV)	−54 (IV)	89.2
RII	218	185	140	−22 (II)	85 (V)	−10 (II)	59.8
RIII	254	187	141	14 (II)	87 (V)	−9 (I)	55.6

AMV: Applied macronutrient variation (kg/ha) from recommended.
$RIFI_{cf}$: *Relative Imbalance Fertilizer Index associated with carbon footprint.*

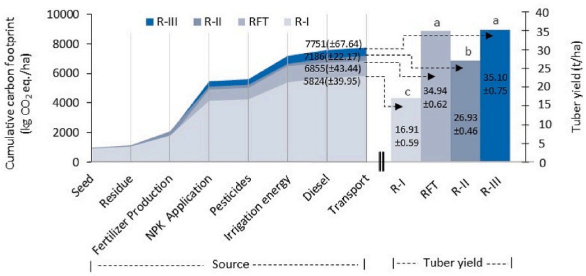

Fig. 3. Source based cumulative carbon footprint per hectare and corresponding tuber yield in different agroclimatic zones of North-West India. (R–I: Undulating plain zone, R–II: Central plain zone, R–III: Western plain zone).

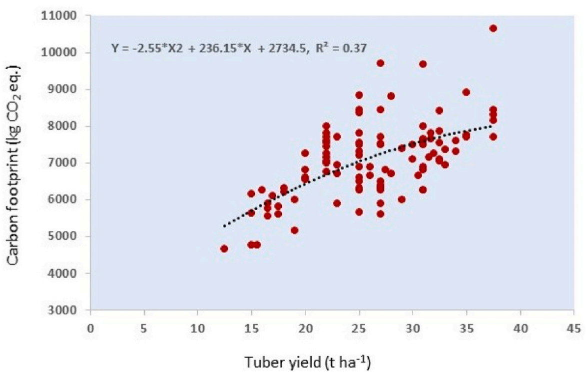

Fig. 4. Tuber yield (2018-19 to 2020-21) as influenced by carbon footprints in potato growing North-West India.

India as additional emissions. It was observed that highest SCC was in zone R–III (US $ 664) followed by R–II (US $ 685.5) and RFT (US $ 594.9). The region R–I (US $ 498.8) was having least values of SCC (Fig. 5). But in order to get net economic balance when this SCC was subtracted from the revenue earned from yield, it was observed that the RFT or the recommended practices gave maximum returns (US $ 2256.1/ha) followed by R–III (US $1998.0/ha), R–II (US $1001.5/ha) and R–I (US $ 70.2/ha).

4. Discussion

4.1. Production practices and resource inputs responsible for carbon footprints

A variation in seed rate observed in three agro-climatic zones can be attributed to the availability of seed and variation in planting

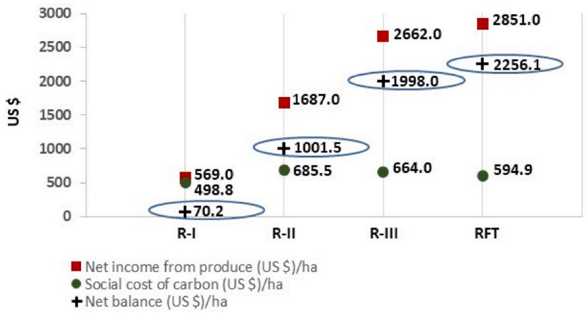

Fig. 5. Per hectare social cost of carbon (@ US $ 86/ton CO_2), net income from yield and net balance (income from yield – social cost of carbon) in potato growing agro climatic zones of North-West India.(Social cost of carbon was calculated as per the estimated values (for India) given by Ricke et al., 2018).

time [21]. The central plain zone produces maximum seed thus is easily available for nearby areas of the zone. Moreover, a major portion of seed produced in this zone is supplied to other parts of the country. The pre-social commitments amongst the seed producers and potato growers of this region, being from same locality, also influence the availability of seed. In other zones because of relatively lower availability of seed, farmers are left with no other option than to reduce the seed rate. Variation in irrigation and fertilization can be attributed to the stretched duration of crop [22]. in R–II and R–III zones, because of which total water as well as nutrient requirement increases as both these components are essential throughout the whole growth period [23]. Long spam exposes the crop for more time thus increasing the probability of disease attacks. This leads to comparatively more pesticide sprays (prophylactic) in zones with stretched duration crop i.e. R–II and R–III.

4.2. *Carbon footprints of potato production system of north-west India and Relative Imbalance Fertilization Index ($RIFI_{cf}$)*

Quantitative variation in carbon footprint per ton tuber yield can be due to variation in level of farming intensification [24], which in turn is directly proportional to inputs like fertilizers [23], irrigation [22], pesticides, and fuels etc., all of which emit greenhouse gases. In comparison to RFT, zone I, II and III emitted more carbon footprint. Relatively more emissions per ton tuber yield in zone R–I from all the sources can be attributed to early harvesting of crop, to get better returns by selling it as off season crop, thus reducing yield that in turn increases carbon footprint value per ton, (as carbon footprint per ton is the ratio of emissions and yield i.e. *Emissions from source (kg CO_2 eq/Tuber yield (t))*. A variation in carbon footprint within various classes of farmers in zone R–III (only in case of seed, energy use and sprays) has been attributed to the variation in their production practices. On the basis of similar studies, many researchers reported carbon footprint amounting 216–286 kg CO_2 eq./t(TY) in Zimbabwe [13], 50–200 kg CO_2 eq./t(TY) in Chile [25] and 77–116 kg CO_2 eq./t(TY) in Netherlands [18]. Major contribution of carbon footprint from fertilizer and irrigation is due to the fact that these two are the major decisive components that are responsible for yield enhancement [[26,27]] and are thus exploited beyond potential to enhance yield. These observations are similar to [[7,28,29]].

A highly significant correlation between applied NPK and carbon footprint was noticed in potato production system of North -West India. Among the fertilizers application, N played a pi-vital role in GHGs emission. These results are similar to the results obtained by [[13,25,30,31]], according to whom N has the greatest impact on carbon footprints among all essential macronutrients as it increase the emissions of N_2O, NO and NH_3, through nitrification, denitrification [32] and volatilization, which occur naturally in soils [33]. Application of fertilizers, especially nitrogenous fertilizer accelerates nitrogen cycle [34] through enhanced microbial activities and biological processes [[32,35,36]]. More carbon footprint due to over fertilization of phosphorus (as an input) in this region [37] can be the reason of positive association of phosphorus application and carbon footprint. Potassium application in soils catalyses various biochemical reactions and thus results in more emissions. This reason holds good for its positive correlation with carbon footprint.

The higher value of $RIFI_{cf}$ in undulating plain zone (R–I) than other two zones in all the three categories of farmers can be attributed to excess and improper use of nutrients [38] in this region. So the reduction of excess nutrient application and balanced fertilizer use are the key mitigation options to reduce such carbon footprint [39]. Variation in carbon footprint had a linear and positive relationship with Relative Imbalance Fertilization Index ($RIFI_{cf}$) which can again be attributed to extent of imbalance fertilization followed [38].

4.3. *Total carbon footprint in relation to yield, social cost and economic balance*

Maximum carbon footprint per hectare was observed in zone R–III followed by R–II, RFT and R–I. This can again be attributed to intensified farming system with more use of inputs that emit greenhouse gases [24]. Such trends have been reported from Zimbabwe by Ref. [13] and from Himachal Pradesh (India) by Ref. [40] in potato. Kashyap and Agarwal [41] also reported the zone wise variation in carbon footprint. Inappropriate/imbalanced use of fertilizers in potato production reported by Ref. [37] may also be one of many reasons for carbon footprint variation.

A polynomial relationship between carbon footprint and yield i.e. an initial sharp increase in carbon footprint, which got slower after a level, with increase in yield can be attributed to high yielding farming system [[24,42]]. However, once the resources are fully exploited and the yield reaches to its potential, the enhanced resource effect becomes negligible. Such type of relationships had been observed earlier also by [[43,44]].

The variation in social cost of carbon in different zones can be attributed to surplus and inappropriate use of nutrients in crop production as these have large cost implications for the farmers [38]. A positive and higher net economic balance was observed in RFT in comparison to other regions which can be attributed to increased yield on following recommended practices and consequently more economic returns. This finding holds in line with the statement that 85 % of reduction in GHG emissions can be realised with already existing technologies [45].

4.4. Mitigation opportunities

Strategies approaches are required to minimize the GHGs emission. Bridging the yield gap between attainable yield and actual yield may be the initial step. Use of "Apposite Macro Nutrient Fertilization (AMNF)" technique developed by Ref. [37] for potato production system in India will enhance tuber yield and lower the GHGs emissions. Introduction and promotion of nitrogen and water efficient varieties will reduce the use of major GHGs emission responsive inputs. Use of solar energy is another option. Production technologies and practices should aim to keep carbon sequestration and carbon footprint ratio more than one. Fertilizer management especially nitrogen fertilizer management should be optimized, and nutrient use efficiency be increased. Creating awareness among the potato growers about GHGs emission and their sources should be encouraged through various Govt. and Non-Govt extension agencies.

5. Conclusion

The present investigation was formulated to find out the carbon footprint of potato production system of north-west India. Another aim was to identify the major source responsible for carbon footprint and to suggest mitigation strategy. The study revealed that there exists a significant variation in carbon footprint of potato production system amongst the major potato growing agro-climatic zones of North-West India in comparison to recommended practices. Since contribution of the factors towards carbon footprint varies regionally, hence strategic efforts for mitigation would be more effective at regional level. Further, findings of the study can be used by planners and policy makers to frame and implement effective strategies for minimizing the carbon footprint since the carbon footprint can be a good indicator of a production system to affirm its sustainability. Moreover, a carbon footprint inventory for the potato production system of northwest India can be developed using the information generated in present investigation. The output of this investigation clearly suggests that 'yes' the carbon footprints are high in North-West potato production system of India due to non-following of recommended practices and thus there is a need to identify, standardize and implement easily adaptable ways of adoption so that the potentially negative impacts on environment can be reduced without a decrease in tuber yield and hence economic returns in the region.

Data availability statement

The data that support the findings of this study are available from the corresponding author (Anil Sharma, email: magotra_anil@rediffmail.com), upon reasonable request.

Annexure A

Physico-chemical properties of soils under study.

Parameters	Undulating plain zone (R–I)			Central plain zone (R–II)			Western plain zone (R–III)			RFT
	C–I	**C-II**	**C-III**	**C–I**	**C-II**	**C-III**	**C–I**	**C-II**	**C-III**	
pH	7.5 (7.3–7.6)	7.3 (6.9–8.2)	7.2 (7.0–7.7)	7.7 (6.7–8.3)	7.5 (6.5–8.4)	7.4 (6.6–8.3)	7.8 (7.6–8.0)	7.6 (6.8–8.0)	7.3 (6.0–8.1)	7.2
OC (%)	0.55 (0.44–0.66)	0.51 (0.35–0.71)	0.44 (0.29–0.56)	0.49 (0.45–0.57)	0.49 (0.17–0.77)	0.50 (0.29–0.69)	0.59 (0.53–0.64)	0.58 (0.35–0.74)	0.62 (0.53–0.69)	0.32
Macronutrients (kg/ha)										
Available Nitrogen (N)	134 (131–137)	135 (100–188)	130 (100–156)	146 (144–150)	149 (62–275)	167 (84–282)	223 (197–254)	201 144-238)	221 (194–247)	222
Available Phosphorous (P)	18 (16–20)	12 (5–22)	16 (9–30)	25 (3–48)	24 (8–109)	25 (6–56)	18 (17–19)	14 (9–26)	18 (8–24)	26
Available Potassium (K)	262 (188–336)	242 (150–462)	239 (146–404)	276 187-389)	241 (113–506)	235 (92–583)	124 (88–150)	116 (50–210)	129 (33–221)	105
Micronutrients (ppm)										
Zinc (Zn)	3.7 (1.3–6.2)	4.4 (2.0–7.9)	4.0 (2.0–6.5)	3.9 (2.6–4.8)	5.0 (1.6–12.8)	5.7 (2.2–14.8)	8.4 (5.5–11.3)	5.9 (1.1–15.6)	10.6 (3.8–17.7)	1.4
Iron (Fe)	9.7 (6.7–12.7)	16.7 (4.8–55.8)	(15.2 8.3–31.8)	43.9 (29.9–64.7)	102.3 (6.2–474.9)	92.8 (12.4–159.8)	22.7 (18.9–28.5)	22.8 (2.1–57.3)	38.1 (25.2–59.4)	
Copper (Cu)	1.5 (1.5–1.6)	1.5 (0.9–1.9)	1.4 (1.1–1.8)	1.9 (1.3–2.5)	6.2 (1.4–15.5)	4.6 (1.1–15.4)	7.0 (4.8–9.5)	4.0 (0.9–19.4)	12.1 (1.1–23.0)	6.3
Manganese (Mn)	12.2 (11.4–13.1)	13.0 (9.3–16.6)	11.8 (7.1–17.4)	21.9 (8.8–35.7)	12.3 (1.4–32.5)	16.6 (1.9–53.4)	10.2 (7.3–13.1)	11.0 (3.4–33.2)	12.4 (4.8–17.6)	1.5

Figures in parenthesis denotes range.

Annexure B

Agro-climatic zone and farmers class wise details of the inputs used for carbon footprints studies zones in North-West India.

	Undulating plain zone (R–I)			Central plain zone (R–II)			Western plain zone (R–III)			RFT
	C–I	C-II	C-III	C–I	C-II	C-III	C–I	C-II	C-III	
General Information										
Seed rate (t/ha)	3.0 (3.0–3.0)	3.4 (3.1–3.8)	3.1 (2.8–3.3)	4.0 (3.5–4.4)	4.2 (3.1–5.3)	4.0 (3.1–5.0)	3.4 (3.0–3.8)	3.8 (3.1–5.0)	3.7 (3.5–4.0)	3.0
Seed treatment	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1
Tuber yield (t/ha)	16.3 (16.3–16.3)	16.4 (12.5–18.8)	17.8 (15.0–25.0)	24.2 (20.0–27.5)	26.9 (20.0–32.5)	27.1 (20.0–35.0)	31.3 (25.0–35.0)	35.5 (31.3–37.5)	36.9 (35.0–37.5)	34.9
Mechanical Field Operations										
Mulcher	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	1 (0–1)	1 (0–1)	1 (1-1)	1 (1-1)	1 (1-1)	0
Rotavator (n) *	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	2 (2-2)	2 (1–2)	2 (2-2)	1
Cultivator (n)	1 (1-1)	1 (0–1)	1 (0–1)	1 (1-1)	0 (0–1)	0 (0–1)	0 (0-0)	0 (0–1)	0 (0-0)	2
Mouldboard plough	0 (0-0)	0 (0–1)	0 (0–1)	0 (0-0)	1 (0–1)	1 (0–1)	1 (1-1)	1 (0–1)	1 (1-1)	0
Disc Ploughing (n)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	0 (0-0)	1 (0–1)	0 (0-0)	1
Planker	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1
Marker cum Fertiliser applicator	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)	1
Ridger	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)	1
Automatic planter	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	1 (1-1)	1 (1-1)	1 (1-1)	0
Ridge plough	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1
Tractor driven digger	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1
Irrigation										
No. of Irrigations	4.0 (4.0–4.0)	4.0 (3.0–4.0)	4.0 (3.0–4.0)	5.0 (5.0–5.0)	5.0 (5.0–6.0)	5.0 (5.0–6.0)	5.0 (5.0–6.0)	5.0 (5.0–6.0)	5.0 (5.0–5.0)	6.0
Pumping depth (ft)	145.0 (140.0–150.0)	163.3 (120.0–190.0)	169.3 (150.0–190.0)	133.3 (120.0–160.0)	136.3 (110.0–180.0)	135.5 (120.0–180.0)	156.7 (150.0–160.0)	159.1 (140.0–180.0)	167.5 (160.0–180.0)	120.0
Nutrient Application										
N (kg/ha)	171.0 (171.0–171.0)	154.5 (96.8–171.0)	164.5 (96.8–196.9)	230.3 (193.5–274.5)	216.1 (171.0–274.5)	218.1 (171.0–274.5)	264.8 (245.3–274.5)	252.4 (171.0–326.3)	254.3 (222.8–297.0)	240.0
P_2O_5 (kg/ha)	172.5 (172.5–172.5)	159.7 (115.0–172.5)	156.1 (115.0–172.5)	191.7 (172.5–230.0)	181.3 (143.8–230.0)	185.2 (115.0–287.5)	191.7 (172.5–230.0)	188.2 (172.5–230.0)	186.9 (172.5–230.0)	100.0
K_2O (kg/ha)	75.0 (75.0–75.0)	108.3 (75.0–150.0)	96.4 (75.0–112.5)	150.0 (150.0–150.0)	136.5 (75.0–150.0)	139.5 (75.0–187.5)	162.5 (150.0–187.5)	136.4 (75.0–150.0)	140.6 (112.5–150.0)	150.0
Biocide Spray										
Weedicide spray (n)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)	1
Fungicides spray (n)	2 (1–2)	2 (1–2)	2 (1–2)	2 (2-2)	3 (1–3)	3 (1–3)	2 (2–3)	3 (2–3)	3 (2–3)	2
Insecticides spray (n)	2 (1–2)	1 (1–2)	1 (1–2)	2 (2-2)	2 (1–2)	2 (1–2)	2 (2–3)	2 (1–3)	2 (1–3)	2

Figures in parenthesis denotes range.

* n denotes number.

CRediT authorship contribution statement

Prince Kumar: Supervision, Conceptualization. **Jagdev Sharma:** Conceptualization. **Anil Sharma:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Mankaran Singh:** Data curation. **Brajesh Nare:** Investigation, Conceptualization. **Manoj Kumar:** Resources.

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.

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