

Carbon footprint and water footprint of rice and wheat production in Punjab, India

Durba Kashyap, Tripti Agarwal*

National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonapat, Haryana 131,028, India

ARTICLE INFO

Keywords:

Life cycle GHG emissions
Nitrogen fertilizer
Irrigated agriculture
Crop residue management
Farm survey
Policy issues

ABSTRACT

Carbon footprint and water footprint assessments can be powerful tools to guide sustainable food production systems. The present study simultaneously quantified the carbon footprint (CF) and water footprint (WF) of rice and wheat production in the five agro-climatic zones of Punjab, India using farm survey data. Further, the variability in CF among the five agro-climatic zones and farm sizes was analysed. The carbon footprint per unit area of rice and wheat was found to be 8.80 ± 5.71 and 4.18 ± 1.13 t CO₂eq/ha respectively. The CF per tonne of rice and wheat was 1.20 ± 0.70 and 0.83 ± 0.23 t CO₂eq/t respectively. Large farms had 39% lower CF per tonne of rice compared to small farms. Residue burning, direct methane emissions and fertilizer use were the most important factors that contributed to the CF of rice and wheat production in Punjab. Nitrogen fertilizer use was identified as the major hotspot for mitigation. The average WF of rice and wheat was found to be 1097 and 871 m³/t respectively. A disparity between CROPWAT estimates of blue WF and actual blue water use was established indicating the need for actual blue WF accounting, particularly for flood irrigated crop production. Additionally, policy measures based on ground situation are discussed and the major role of local government policies in mitigating carbon and water footprint is highlighted.

1. Introduction

Food production has large impacts on both global warming and freshwater consumption. The agriculture, forest and other land use (AFOLU) sector, which accounted for 24% of the global greenhouse gas (GHG) emissions in 2010, is the second largest sectoral GHG emitter (Smith et al., 2014). Agriculture is also the largest freshwater user accounting for 70% of global freshwater withdrawals, and 95% of water withdrawals in some developing countries (FAO, 2017). India, a leading food producer and predominantly agrarian nation, is the third largest GHG emitter (WRI, 2014), and a severely water-stressed country. It is among the 17 highly water-stressed countries in the world, with three times higher population than the combined population of all the other 16 countries (WRI, 2019). With its growing population, India is facing the twin challenge of increasing food production, given its limited water resources, while mitigating the associated GHG emissions.

Carbon footprint (CF) and water footprint (WF) are two widely used 'pressure indicators' that measure the human use of natural resources and the anthropogenic emissions; and can be used to direct mitigation policy (Ercin and Ertug Hoekstra, 2012). Few studies have utilised farm survey data for CF assessments (Yan et al., 2015; Arunrat et al., 2016; Zhang et al., 2017; Tahmasebi et al., 2018); and studies reporting WF of

crops using farm level data are negligible (Cao et al., 2018; Ghosh and Chakma, 2019). Previous estimates of GHG emissions from crop production using life cycle assessment (LCA) approach in India were also based on secondary data sources (Pathak et al., 2010; Vetter et al., 2017; Benbi, 2018). Moreover, CF accounting at a high resolution, including crop management practices, like residue burning, has not been reported earlier in any of the LCA based study from India. Variability in CF among agro-climatic regions or farm sizes has not been studied previously in India. It is important to study regional variations to identify the hotspots across regions so that mitigation efforts can be specifically and effectively targeted. In this regard, primary data can capture the variability that is lost when statistical data is used (Schafer and Blanke, 2012). Based on first-hand information, survey-based studies reflect the existing regional diversity in farming practices that can be critical in environmental assessments (Zhang et al., 2017; Tahmasebi et al., 2018). This becomes significant in case of production of staple crops like rice and wheat that are produced in large quantities.

The study region, Punjab, also known as 'the granary of India' is the highest contributor to the central pool of grains in India (Government of India, 2018). It contributed 25.5% and 35.5% respectively in the central pool of rice and wheat during 2018–19 (ENVIS, 2020). The high productivity of the region was made possible due to introduction of

* Corresponding author.

E-mail address: tripti.niftem@gmail.com (T. Agarwal).

<https://doi.org/10.1016/j.agsy.2020.102959>

Received 18 May 2020; Received in revised form 21 September 2020; Accepted 23 September 2020

Available online 12 October 2020

0308-521X/ © 2020 Elsevier Ltd. All rights reserved.

irrigation, high yield variety (HYV) seeds, and consequent higher inputs of fertilizers and chemicals (Sarkar and Das, 2014). However, post green revolution, this has caused the over-exploitation of natural resources to the extent that sustainability of the present farming system of Punjab is uncertain unless major steps are taken towards improvement (Hira, 2009; Benbi, 2018).

Rice and wheat have the largest blue water footprints among crops (Mekonnen and Hoekstra, 2011). Water consumption is directly linked with the GHG emissions of groundwater irrigation, and therefore, there is an opportunity for concurrent mitigation of both. In Punjab, 99.3% of the gross cropped area is irrigated; of this, groundwater irrigation accounts for 71% (Statistical Abstracts of Punjab, 2019). Rice cultivation has expanded into non-suitable porous and coarse soils solely due to irrigation (Chauhan et al., 2012). Therefore, simultaneous assessment of CF and WF, based on farmer inputs, has the potential to reveal key insights such as the disparity between theoretical and actual water consumption. This disparity can be critical in policy framing. This study simultaneously estimated the CF and WF of crop production using farm survey data. CF and WF was previously estimated for tomato (Page et al., 2012) and pumpkin (Schafer and Blanke, 2012) using primary data of crop production. To the best of our knowledge, no such studies on grain production have been attempted globally. Therefore, the present study was planned to address this gap by quantifying both CF and WF of rice and wheat using farm survey data. It also aimed to analyse the variability in CF of different agroclimatic zones and farm sizes; assess the contribution of different inputs and suggest policy measures for mitigation of GHG emissions and water consumption from agriculture in a local as well as global context.

2. Materials and methods

2.1. Study area

The study was conducted in the state of Punjab (extending from 29° 32' to 32° 32' N latitude and 73° 55' to 76° 50' E longitude) located in the north-western part of India. A part of trans Indo-Gangetic plains, Punjab is divided into five agro-climatic zones (ACZ) i.e. sub-mountain undulating zone (Zone I), undulating plain zone (Zone II), central plain zone (Zone III), western plain zone (IV) and western zone (V). Zone I & II are humid to sub-humid with an average rainfall of 900 mm; Zone III is semi-arid to dry sub-humid with mean rainfall of 561 mm; Zone IV and V are arid to extremely arid with 360 mm rainfall on an average (ENVIS, 2020). For the purpose of survey, one representative district of each ACZ was selected (Fig. 1).

2.2. Data collection

The study was aimed at understanding variability of carbon footprint among different agroclimatic zones; therefore, the primary data collection was done from one representative district from each agro-climatic zone. The representative districts and number of valid farmers' responses in each district are presented in Fig. 1. Convenience random sampling was used for the purpose of survey. The farmers were approached through the Directorate of Extension Education, Punjab Agriculture University (PAU), Ludhiana and Krishi Vigyan Kendras (KVKs) to conduct the survey. KVKs are agriculture extension centers which serve as a link between the Indian council for Agricultural Research (ICAR) and farmers. Besides this, farmers were also approached personally. Questionnaires administered through personal interview were used for the survey data collection conducted during the months of June–July 2018. This study is based on farmers' recall of the previous cropping season. In total, valid responses were obtained from 206 rice growing farmers and 237 wheat growing farmers. Details of data collected for CF and WF assessment are presented in Table 1.

2.3. Carbon footprint assessment

2.3.1. Functional units and system boundaries

The CF assessment for rice and wheat production was carried out using LCA approach based on the PAS 2050:2011 protocol (BSI and Carbon Trust, 2011). The system boundary was set from 'cradle to farm-gate'. Carbon footprint was accounted for individual inputs used in seeding to harvesting stages of crop production. Land-use change (occurred more than 20 years prior to assessment) and changes in soil carbon content have been excluded from the assessment as per PAS 2050 guidelines. Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) emissions were accounted by converting into CO₂eq using the latest Intergovernmental Panel on Climate Change's (IPCC) 100-year global warming potential (GWP) coefficients of 1, 28 and 265 respectively (IPCC, 2013). Two functional units i.e. carbon footprint per unit area expressed as tonnes CO₂-equivalents per hectare (t CO₂eq/ha) and carbon footprint per unit weight expressed as tonnes CO₂-equivalents per tonne of grain (t CO₂eq/t) were used for CF accounting.

2.3.2. Emission quantification protocol

GHG emissions due to crop production included both direct (N₂O emissions due to N content in fertilizers, incorporated crop residue and farmyard manure; CH₄ emissions due to rice cultivation and energy (fuel) use in farm machinery) and indirect emissions (production of agrochemicals and electricity usage) associated with the inputs (Yan et al., 2015). The list of emission factors (and their sources) used for CF quantification is given in Supplementary Table S1. Emission factors (EFs) used for direct CH₄ and N₂O from soil were based on field level experimental studies in Punjab. State-specific EF was used for energy, while country-specific EFs were used for fertilizers, fuel, indirect N₂O emissions (due to leaching and volatilization) from the soil. The other EFs were based on global studies or IPCC default values.

Firstly, the GHG emissions associated with inputs including the seeds, agrochemicals, electricity, and farm machinery were calculated using the following equation:

$$CF_A = \sum (A_i * EF_i) \quad (1)$$

Where CF_A is the sum of GHG emissions (per hectare) due to i^{th} activity/input in t CO₂-eq. A_i is the activity data/amount of i^{th} activity/agricultural input (fertilizer (kg N/ha; kg P₂O₅/ha), pesticide (kg/ha), diesel (l/ha), energy (kW.h/ha)) and EF_i is the emission factor of the i^{th} process (in t CO₂-eq per unit volume or mass).

The energy consumption for irrigation by each farmer (E_c) (in kW.h) was calculated using the following equation:

$$E_c = hp * n * d * F_c$$

Where hp is the energy rating of pump (in horsepower), n is the number of pumps, d is the approximate duration of pump operation in entire crop season (in hours), F_c is the conversion factor (0.75) of horsepower hour (hp.h) into kilowatt-hour (kW.h). hp , n , d was taken from the survey data.

Direct and indirect N₂O emissions were calculated using the following equations:

$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect} \quad (2)$$

$$N_2O_{direct} = (F_{SN} + F_{ON} + F_{CR}) * EF_1 * \gamma_{N_2O} \quad (3)$$

$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)} \quad (4)$$

$$N_2O_{(ATD)} = (F_{SN} * EF_4 * Fras_{GASF} + F_{ON} * EF_4 * Fras_{GASM}) * \gamma_{N_2O} \quad (5)$$

$$N_2O_{(L)} = (F_{SN} + F_{ON} + F_{CR}) * EF_5 * Fras_{LEACHING} * \gamma_{N_2O} \quad (6)$$

Where, F_{SN} , F_{ON} and F_{CR} are the amount of N in synthetic fertilizer, animal manure and crop residues (above-ground and below-ground) respectively added to soils (in kg N/crop season). $N_2O_{(ATD)}$ and $N_2O_{(L)}$ are N₂O emissions from atmospheric deposition, and leaching and

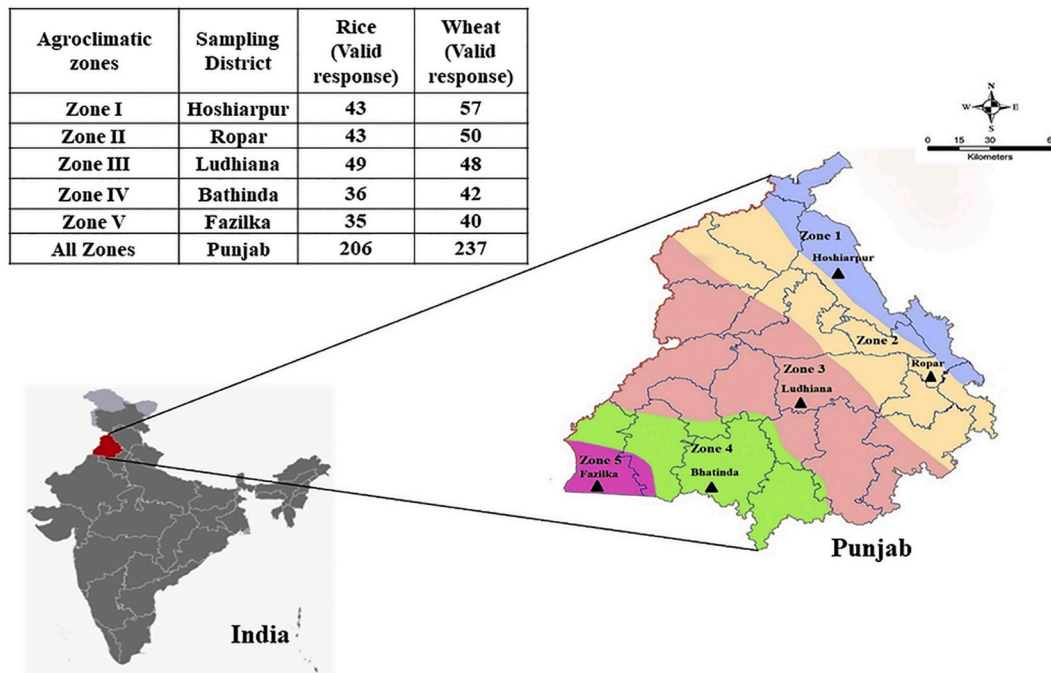


Fig. 1. Study area and survey details including number of valid farmers' responses for rice and wheat.

runoff of nitrogen additions from managed soils respectively. EF_1 is the emission factor for N_2O emissions from N inputs (kg N/input); EF_4 and EF_5 are the emission factors for N_2O emission due to volatilization, and leaching and run-off N from fertilizer and manure respectively. $Fras_{GAS}$, $Fras_{GASM}$, and $Fras_{LEACHING}$ are the fraction factors of atmospheric deposition of N volatilized from mineral fertilizer, organic materials, and leaching from managed soil; γ_{N_2O} (44/28) is the mass conversion factor for N_2 to N_2O (IPCC, 2006).

$$CF_{N_2O} = N_2O_{total} * 265 \quad (7)$$

Where CF is the GHG emission due to N_2O and 265 is the GWP of N_2O (IPCC, 2013).

Direct methane emission due to submerged paddy cultivation was calculated using the following equation (IPCC, 2006):

$$CF_{CH_4} = EF_d * t * A * 28 \quad (8)$$

Where, EF_d is the adjusted daily emission factor for a particular harvested area; t is the duration of crop growth (taken as 140 days for most commonly grown rice varieties in Punjab); A is the area harvested in hectares (ha); 28 is the GWP of CH_4 (IPCC, 2014).

$$EF_d = EF_c * SF_w * SF_p * SF_o \quad (9)$$

Where EF_c is baseline emission factor for continuously flooded fields

without organic amendments, SF_w and SF_p are scaling factors to account for the differences in water regime during and before the cultivation period respectively. SF_o is the scaling factor to account for both type and amount of organic amendment applied. EF_c and other scaling factors' values are tabulated in Supplementary Table S1. SF_o was calculated for each farmer based on the following equation (IPCC, 2006):

$$SF_o = \left(1 + \sum_i ROA_i * CFOA_i \right)^{0.59} \quad (10)$$

Where ROA_i is the rate of application of organic amendment in t/ha; $CFOA_i$ is the conversion factor for organic amendment i. $CFOA_i$ was taken as 0.29 for straw incorporation (for straw incorporated for > 30 days) and 0.14 for farmyard manure incorporation (IPCC, 2006).

GHG emission due to crop burning was calculated using the following equation (IPCC, 2006):

$$CF_B = Y * R_f * DM_f * B_f * O_f * EF \quad (11)$$

Where Y is the crop yield based on survey data, R_f is residue to crop ratio, DM_f is dry matter fraction, B_f is fraction burnt. O_f is fraction oxidized. EF is the emission factors for CO_2 , CH_4 and N_2O emitted while burning (Supplementary Table S1). The emission from crop residue burning was calculated for each farmer who practiced residue burning.

Table 1
Variables and data sources considered for carbon footprint and water footprint assessment.

Variable	Data source	Granularity
Grain yield and farm size	Farm survey (this study)	Individual farmer
Farm inputs (seed, fertilizer, pesticides, farm yard manure)	Farm survey	Individual farmer
Diesel for farm operations	Farm survey	Individual farmer
Energy for irrigation (energy rating of pump, no. of pumps and duration of operation)	Farm survey	Individual farmer
Crop residue management practices (data on residue burning, incorporation, removal)	Farm survey	Individual farmer
Climate data	Regional research stations, regional extension centre (Zone I & II)	District
Soil parameters	Calculated online using soil & clay percentages from Singh et al. (2009); (Song et al. (2015) for Zone V)	Agro-climatic zone
Crop coefficients	Kaur et al., 2017 (wheat); Default values of CROPWAT (rice)	State Global

Finally, the carbon footprint per unit area (in kg CO₂eq/ha) for each farmer was calculated as:

$$CF_{\text{per unit area}} = CF_A + CF_{N_2O} + CF_{CH_4} + CF_B$$

The carbon footprint per unit weight (in kg CO₂eq/kg) for each farmer was calculated as:

$$CF_{\text{per unit weight}} = \frac{CF_{\text{per unit area}}}{\text{Yield}}$$

2.3.3. Data processing and statistical analysis

Data processing was performed using XLSTAT software. Since the CF for rice and wheat did not follow normal distribution, the Kruskal-Wallis test was used to check the differences between regions and farm size classes. The level of significance was defined at $p < 0.05$.

2.4. Water footprint calculations

The methodology described by Hoekstra et al. (2011) was used for calculating the water footprint. Crop evapotranspiration (ET_c) and effective rainfall (Pe_{eff}) were estimated using the 'irrigation schedule option' in FAO-CROPWAT 8.0 software which were further used to calculate green and blue WF using yield data from farm survey. Soil input parameters (Table 1) were calculated for each zone except Zone V which has loamy sand soil type for which parameters were adopted from Song et al. (2015). The sand and clay percentage for each zone (I to IV) was derived from Singh et al. (2009) and was entered into online soil hydraulic properties converter (<http://resources.hwb.wales.gov.uk/VTC/env-sci/module2/soils/soilwatr.htm>) to estimate parameters that are used as input to CROPWAT. The details of data and other inputs used in CROPWAT are presented in Supplementary Tables S2, S3 and S4.

The greywater component (WF_{grey} , m³/t) in the water footprint is the amount of water required to dilute pollution. WF_{grey} was calculated as:

$$WF_{\text{grey}} = \frac{(\alpha \times AR) / (C_{\text{max}} - C_{\text{nat}})}{Y}$$

Where, AR is the chemical application rate to the field (in kg/ha). It was derived from survey data (kg N/ha) per farmer, α is the leaching run-off fraction set at 10% (Hoekstra et al., 2011), C_{max} is the maximum acceptable concentration of a pollutant (nitrogen) for a given water body which was taken as 10 mg/l (EPA, 2005), C_{nat} , the natural background concentration of nitrogen (mg/l) was set at 0. Y is the crop yield (t/ha) derived from survey data. The mean yield and AR per farmer were taken for each zone.

3. Results

3.1. Carbon footprint of rice and wheat

The mean carbon footprint per unit area of rice production in Punjab was found to be 8.80 ± 5.71 t CO₂eq/ha and the CF per unit weight was 1.20 ± 0.70 t CO₂eq/t. The CF of wheat was 4.18 ± 1.13 t CO₂eq/ha and 0.83 ± 0.23 t CO₂eq/t. Thus, the CF of the rice-wheat system in Punjab was 12.98 ± 5.82 t CO₂eq/ha and 2.02 ± 0.78 t CO₂eq/t. The CF of rice and wheat are presented in Table 2. The CF distribution for rice and wheat was positively or right-skewed (mean > median) with a Pearson coefficient of skewness (sk) equal to 1.31 and 0.34 respectively. The CF of rice was highly skewed indicating that most farmers had a relatively lower CF, while, few farms having very high CF increased the mean CF.

3.2. Contribution of different inputs

Rice residue burning was the highest contributor (36%) to the CF of

rice production in Punjab followed by nitrogen (N) fertilizers (19%), of which 10% was indirect emissions due to production of fertilizers, while soil N₂O emissions contributed 9% (emissions under 'N fertilizers' comprise both indirect emissions from urea manufacturing and N₂O emissions from soil, due to 18% N present in DAP and 46% N in urea), methane emissions due to submerged paddy (17%), and energy use for irrigation (14%). Other factors contributed less than 10% to GHG emissions of rice production. The percentage contribution of different sources to the CF of rice and wheat is presented in Figs. 2 and 3 respectively. In the case of wheat production, N fertilizer use (57%) was the single largest contributor to GHG emissions. Unlike rice production, N₂O emissions contributed only 6% to this, while the rest of the emissions (51%) was due to fertilizer production. Other sources i.e. residue burning (10%), P fertilizers (10%), diesel (9%) and energy (7%) had almost similar contributions. The share of crop residue and FYM (Farm Yard Manure) incorporation was 2% and 6% respectively for rice and wheat. The share of pesticides and seed in CF was relatively low (< 3%) for both rice and wheat. GHG emissions from various inputs and average amounts of major agricultural inputs are presented in Supplementary Tables S5–S8.

3.3. Variation of CF among regions and farm sizes

The carbon footprint of both rice and wheat was found to be significantly different among the five zones. The pairwise comparison between CF per unit area and CF per unit weight of rice and wheat production in each zone is presented in Table 2. CF of the semi-arid zones (Zone IV & V) was found to be relatively higher, as compared to the other three regions. On the other hand, Zone I accounted for the lowest CF for both rice and wheat.

CF per tonne of rice was significantly different ($p = 0.001$) among the farms of different sizes (Table 3). In particular, the pairwise comparison revealed CF per tonne in large farms differed significantly from small farms. The average CF of rice in large farms (0.81 ± 0.41 t CO₂eq/t) was found to be 39% lower than small farms (1.32 ± 0.79 t CO₂eq/t). However, no significant difference was found between CF per hectare of rice between different farm sizes. For wheat production, no significant difference was observed between the CF of wheat production among different farm sizes.

3.4. Water footprint of rice and wheat

The water footprint of rice and wheat for Punjab (average of all five regions) for the year 2017–18 was found to be 1097 and 871 m³/t respectively. Green, blue, and grey WF contributed 63%, 19% and 17% respectively to the total WF of rice; and 15%, 52% and 33% respectively in case of wheat WF. However, based on energy consumption for groundwater irrigation, derived from survey data, it was found that the actual blue WF is much higher than model-based estimates. WF of rice and wheat for each region is represented in Fig. 4 and Supplementary Table S9. The variations in WF of rice and wheat across agroclimatic zones were found to be minimal, except for Zone II, which had the highest WF due to lower yields as compared to other regions.

4. Discussions

4.1. Carbon footprint of rice and wheat

Previous studies reporting CF of rice and wheat in India (Pathak et al., 2010; Vetter et al., 2017, 2019) have reported lower values as compared to this study. This could be because the afore-mentioned studies used national average inputs. Resource consumption in the study area (Punjab) is much higher as compared to India (average). The average fertilizer (N, P, K) consumption and agricultural energy consumption in Punjab was respectively 82% and 28% higher as compared to the national average for the duration 2015–2018 (Gol, 2018).

Table 2
Carbon footprint of rice and wheat production in different agro-climatic zones of Punjab.

Region	Rice			Wheat		
	Yield (t/ha)	CF per unit area (tCO ₂ eq/ha)	CF per unit wt. (tCO ₂ eq/t)	Yield (t/ha)	CF per unit area (tCO ₂ eq/ha)	CF per unit wt. (tCO ₂ eq/t)
Zone I	7.50 ± 0.85	5.71 ± 2.88 ^d	0.77 ± 0.38 ^c	5.17 ± 0.63	3.38 ± 0.95 ^b	0.67 ± 0.22 ^b
Zone II	6.34 ± 0.96	8.54 ± 4.82 ^{bc}	1.35 ± 0.70 ^a	4.81 ± 0.6	4.25 ± 1.09 ^a	0.90 ± 0.26 ^a
Zone III	7.36 ± 0.59	7.05 ± 4.05 ^c	0.95 ± 0.52 ^b	5.22 ± 0.42	4.16 ± 0.78 ^a	0.80 ± 0.15 ^a
Zone IV	7.81 ± 0.59	11.22 ± 6.7 ^{ab}	1.44 ± 0.89 ^a	5.23 ± 0.50	4.72 ± 1.25 ^a	0.89 ± 0.17 ^a
Zone V	7.82 ± 0.62	12.88 ± 6.95 ^a	1.63 ± 0.85 ^a	5.20 ± 0.53	4.68 ± 1.01 ^a	0.91 ± 0.23 ^a
Punjab Mean	7.33 ± 0.91	8.80 ± 5.7	1.20 ± 0.7	5.12 ± 0.56	4.18 ± 1.13	0.83 ± 0.23
Median	7.41	6.12	0.86	5.19	4.03	0.80
Range	3.58–9.88	3.78–26.56	0.51–4.22	3.48–7.04	1.64–7.65	0.28–1.49

CF values with no letter (superscript) in common are significantly different by Kruskal Wallis test at $\alpha = 5\%$ level of significance. (For e.g. in the column Rice FCF, CF of Zone II is significantly different from CF of Zone I and Zone V). The values in bold are the mean, median and range for the entire study area of Punjab, while the other values (not in bold) are for each zone.

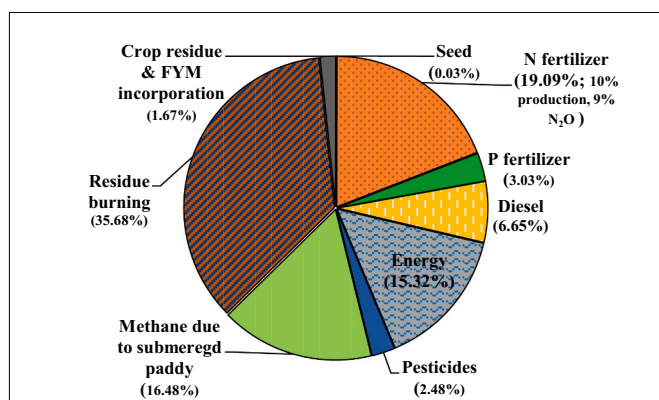


Fig. 2. Percentage contribution of different sources to the CF of rice.

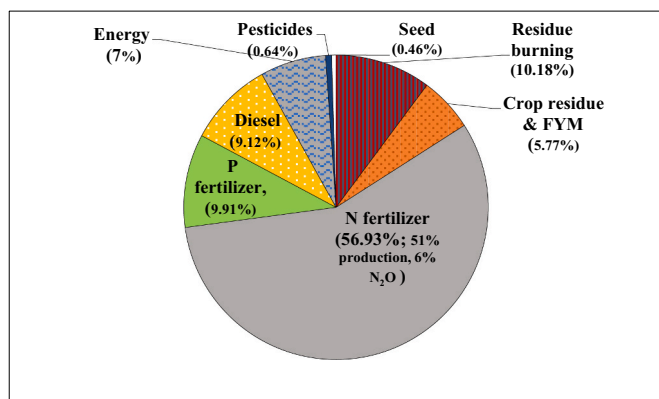


Fig. 3. Percentage contribution of different sources to the CF of wheat.

Moreover, the India specific EF used for fertilizers in this study could be higher than the previous studies. Even though, EFs are not mentioned in the afore-mentioned studies, the study by Vetter et al. (2017) used cool farm tool, which estimates CF based on global average EF. According to Kool et al. (2012), the CF of fertilizer production in India and China is much higher than the rest of the world. Further, unlike previous studies, this study is conducted at a higher resolution and includes emissions from banned practices like residue burning. Overall, emission per hectare of rice and wheat in this study was higher compared to several studies globally. Only a handful of studies had higher CF values than this study for rice (Thanawong et al., 2014; Arunrat et al., 2016; Johnson et al., 2016; Zhang et al., 2017) and wheat (Zhang et al., 2017). However, studies reporting CF from different regions cannot lead to meaningful comparisons as there are differences in management practices, inputs, soil, and climatic conditions, use of emissions factors

Table 3

CF of rice and wheat for different farm size classes.

Crop	Farm size class	Small (< 2 ha)	Medium (2–10 ha)	Large (> 10 ha)
Rice	No. of farms	67	117	22
	CF (t CO ₂ eq/ha)	9.37 ± 5.95 ^a	8.97 ± 5.86 ^a	6.14 ± 2.98 ^a
	CF (t CO ₂ eq/t)	1.32 ± 0.79 ^b	1.21 ± 0.74 ^{ab}	0.81 ± 0.41 ^a
	Yield (t/ha)	7.11 ± 1.04	7.41 ± 0.84	7.62 ± 0.76
Wheat	No. of farms	63	137	37
	CF (t CO ₂ eq/ha)	4.40 ± 1.13 ^a	4.09 ± 1.13 ^a	4.12 ± 1.09 ^a
	CF (t CO ₂ eq/t)	0.89 ± 0.23 ^a	0.80 ± 0.23 ^a	0.80 ± 0.22 ^a
	Yield (t/ha)	5.02 ± 0.65	5.14 ± 0.54	5.19 ± 0.47

n indicates the number of farms. Means not sharing any letter (superscript) are significantly different by Kruskal Wallis test at level of significance ($\alpha = 5\%$). *Farm sizes categorized based on PIB (2019).

etc., which account for differences in CF. Also, for mitigation-oriented comparison of GHG emissions and usage of resources, CF per unit area is a better indicator than CF per unit weight, as it truly reflects the magnitude of emissions, and is not masked by yield.

4.2. Contribution of different sources

Nitrogen (N) fertilizer use, crop residue burning, methane emissions, electricity and diesel consumption were the prominent factors contributing to GHG emissions from rice and wheat production in Punjab. In Punjab, most of the wheat straw is removed after harvest and used as fodder, while rice straw being unsuitable as fodder is removed before the next crop (wheat) is sown. In Punjab, there has been a 173% increase in GHG emissions due to crop burning (particularly rice) between 1980 and 2013, primarily due to farm mechanization, (combined harvesters) that generates enormous amounts of unused stubble, that is burnt to save cost and time (Benbi, 2018). However, being a banned practice, emissions associated with stubble burning are not adequately represented in secondary databases. In Punjab, rice is immediately followed by wheat. The N in rice crop residue, if incorporated in wheat would lead to N₂O emissions. Crop residue incorporation contributed 5.8% (0.24 t CO₂eq/ha) to GHG emissions from wheat cultivation, as compared to 1.7% (0.15 t CO₂eq/ha) in rice. With the ban on stubble burning and government initiatives to incorporate rice stubble using 'happy seeder technology', this percentage is expected to rise, indicating a trade-off between emissions due to residue burning and residue incorporation. Other alternatives which require the collection and transportation of residues are not popular, as they are uneconomical and cumbersome (Lohan et al., 2018).

Overall, nitrogen fertilizer use in rice and wheat production respectively emitted 1.72 ± 0.39 t CO₂eq/ha and 2.39 ± 0.5 t CO₂eq/ha. Of this, indirect emissions due to fertilizer production comprised

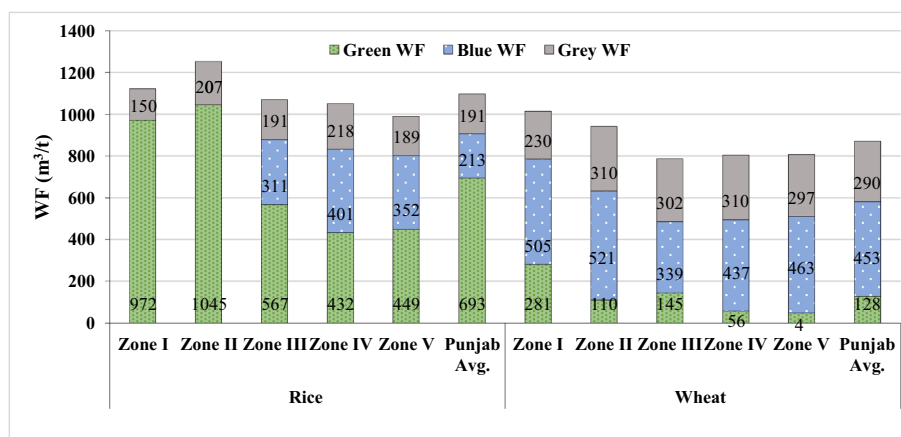


Fig. 4. Green, blue, and grey WF (in m³/t) for rice and wheat production in each zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

53.3% and 45.6% for rice and wheat respectively, and the rest was accounted for by direct field emissions from fertilizer application. N₂O emissions from soil in rice and wheat respectively amounted to 0.80 ± 0.25 and 1.3 ± 0.35 t CO₂eq/ha; of which fertilizer use contributed the majority (85% in rice, 83% in wheat), while farm yard manure and crop residue incorporation accounted for the rest. Therefore, the difference in N₂O emissions in rice and wheat stemmed primarily from difference in emission factors used (EF for wheat was 1.6 times higher than rice EF). The average N fertilization rate (including both urea and DAP) was found to be 36% and 18% higher than the recommended dose of N for rice and wheat respectively in Punjab (PAU, 2017). The use of HYV seeds require higher fertilizer and water inputs, which lead to higher CF and grey WF. The increase in use of fertilizers over time in Punjab to boost productivity is reflected in the GHG emission trends (Benbi, 2018) and grey WF. N₂O emissions were found to increase exponentially beyond a fertilization rate of 200 kg N/ha (Linguist et al., 2012). In the case of Punjab, the fertilization rate is presently below 200 kg N/ha; however, if the current increasing trend in fertilization continues, the GHG emissions are likely to increase at an accelerated rate. With the declining fertilizer N use efficiency (Benbi, 2018), this might be a possibility in the future, if steps to decrease fertilizer use are not taken on an urgent basis. Therefore, reducing N fertilizer use is the greatest hotspot for mitigation in the study area. Even though, increase in yield has been suggested as a mitigation measure to justify the negative environmental impacts associated with higher inputs (Ali et al., 2017), the amount of inputs (including water) required to achieve a certain yield level needs to be carefully considered and region specific benchmarks need to be set. Moreover, in this study, yield and N use was found to be weakly correlated in the case of rice ($\rho = 0.21$) and no correlations ($\rho = 0.01$) were found between wheat yield and N use.

4.3. Variation in farm size classes and agroclimatic zones

In this study, large rice farms (> 10 ha) were found to have lesser GHG emissions per tonne of rice, than small farms (≤ 2 ha). Since, yield based CF of rice was found to differ significantly, difference in yield was investigated between farm size classes. Farm size was found to be weakly correlated with rice yield ($\rho = 0.14$), and wheat yield ($\rho = 0.2$). No significant differences were found between rice yield of different farm size classes ($p = 0.08$), even though, large farms had 7% higher yields than smaller farms. In addition, the energy use of large farms was found to be 60% lower than small farms. This, in combination with higher yields, could explain the lower CF per tonne in large farms. In the case of wheat, no significant difference was found between wheat CF of different farm size classes. This could be because management

practices in wheat production did not differ with farm size. During the survey, it was noticed that several farmers owning (or leasing) large areas had segmented land holdings, which might be due to the acquittal of new lands as farmers are quitting agriculture. This could partially explain the similarity in CF among different farm sizes in this study. Since, the definition of farm size classes is ambiguous in different studies (Yan et al., 2015; Arunrat et al., 2016; Johnson et al., 2016), it is difficult to reach a global consensus on the effect of farm sizes on GHG emissions. Therefore, mitigation-oriented assessments of CF variation with farm size classes carried out on a regional or national basis would be more suitable for policy decisions.

The variation in major sources of emission among different zones are presented in Figs. 5 and 6. Emissions due to rice residue burning reflected the same order as rice CF (& wheat CF per tonne) among zones (Zone V > IV > II > III > I), indicating a strong correlation between CF and burning of crop residue of rice ($\rho = 0.75$; $p \leq 0.0001$) and wheat ($\rho = 0.70$; $p \leq 0.0001$). Emissions due to residue burning varied the most among different zones. Therefore, residue burning can be accounted for as the primary determinant of variation of CF among regions. Zone V, which had the highest crop residue burning emissions, was also found to have ~20% lower literacy rates than other zones (Statistical Abstract Punjab, 2017). This indicates the role of socio-economic development and education in adoption of certain management practices. It could also provide cues on region identification for awareness building for mitigation. With respect to inputs, less variation was found among different agroclimatic zones. Zone I was had the

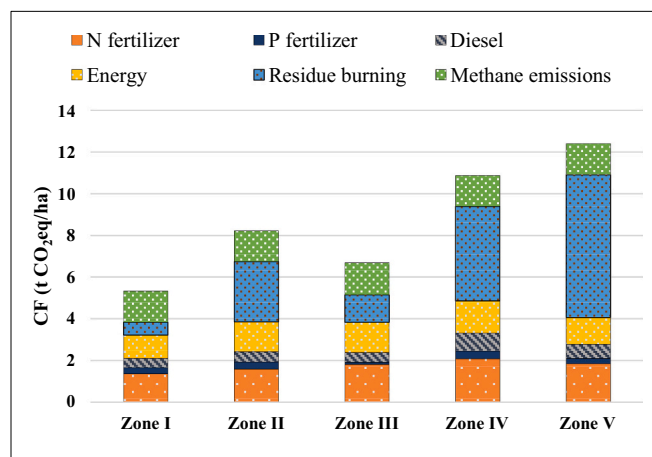


Fig. 5. Zone-wise CF variation in rice production due to contribution of major sources.

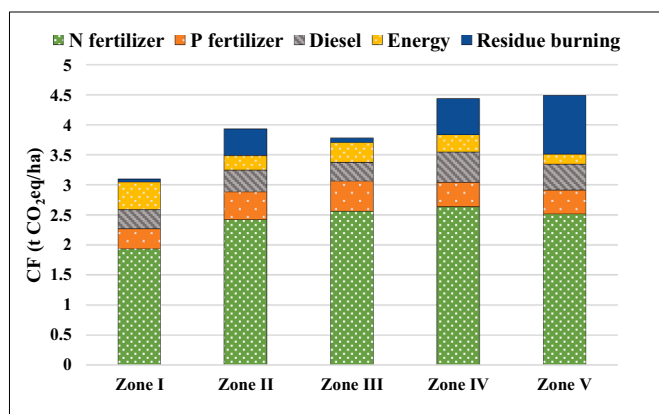


Fig. 6. Zone-wise CF variation in wheat production due to contribution of major sources.

lowest N fertilization rates, which might be due to the sequential cropping pattern of maize/rice-potato-wheat (in most of the surveyed farms), where, fertilizer application in one short duration crop (potato) compensates for fertilizer application in the successive crop (e.g. wheat). Zone IV and V were found to have 62% and 42% higher diesel consumption for rice and wheat respectively as compared to other zones. This could be because these zones are semi-arid with sandy soil, that causes resistance to tractors, that consequently consume more fuel. Despite some zones (I & II) receiving higher rainfall, there was no significant difference between emissions due to irrigation energy use among regions ($p = 0.49$). This is contrary to the common assumptions that higher rainfall would translate to lower groundwater consumption. Therefore, this study proves that geo climatic conditions are not a major factor affecting GHG emissions of crop production and water consumption. Further, if management practices do not vary, targeting environmental assessments and mitigation at the resolution of agroclimatic zones will not be effective.

4.4. Water footprint

On comparison of WF values from this study with previously reported WF from Punjab (Mekonnen and Hoekstra, 2010), it is apparent that the WF for rice and wheat in Punjab has reduced over the years. This is primarily due to an increase in yield from 5.3 t/ha (averaged over 1996–2005) to 7.4 t/ha for paddy rice and from 4.2 t/ha to 5.1 t/ha for wheat (ENVIS, 2018). However, the situation for grey WF has worsened over time, despite the increase in yields. This clearly indicates the rampant use of fertilizers to improve productivity over time. Water footprint of rice and wheat among five zones appeared contradictory as the regions receiving higher rainfall (Zone I & Zone II) were found to have a relatively higher WF as compared to regions (Zone V) that are arid and have a high evapotranspiration. The lower yields and small landholdings in Zone II could partially explain this contradiction.

4.4.1. Accuracy of theoretical WF estimates

The disparity between theoretical estimates from CROPWAT model and actual water use in the field could be derived from the findings of this study. The blue WF of rice in Zone I and Zone II was found to be 0 m³/t (Supplementary Table S9), suggesting zero requirement of irrigation for rice in those zones. This leads to the conclusion that Zone I and Zone II in Punjab are more favorable for rice growing since groundwater abstractions for irrigation is not required. However, the ground situation is quite contrary. The survey of farmers in these regions revealed that rice is irrigated using groundwater for approximately 40–60 days with an average electricity consumption of 1142 kWh/ha and 1435 kWh/ha respectively in Zone I and II. Thus, the actual irrigation water use is much higher in these zones than

CROPWAT estimates (Kashyap and Agarwal, 2020). Depleting groundwater resources is a concern in both the regions (CGWB 2011; 2013). Due to topography, these zones have erosion prone soil which has low water holding capacity, thus causing rainwater runoff instead of seepage (Aggarwal et al., 2009). Therefore, the water assumed to be received by the crops might actually be lost as runoff due to topography. The CROPWAT model estimates vary from the actual water use since the differences in topography are not accounted for in the model. This could also be a reason for the lowest levels of groundwater in certain pockets of Zone I and II in the entire state of Punjab (50–70 m below ground level) (Sood, 2016), despite receiving high rainfall. This highlights the importance of factors beyond climate that play a role in actual water consumption during crop production. More importantly, it shows that higher rainfall in a region does not always lead to blue water saving, as rainwater does not necessarily translate into available water for fulfilling the crop water requirement.

4.5. Policy suggestions for mitigation based on ground situation

There has been a shift in cropping pattern in Punjab in which water intensive rice-wheat cropping system has replaced the traditional maize-wheat system over time (Sarkar and Das, 2014). This was augmented by a shift to groundwater irrigation supported by free electricity leading to a huge expansion of area under rice cultivation. Rice in Punjab is mostly grown under continuously flooded conditions which is also a source of CH₄ emissions. Submerged paddy production is preferred by farmers in Punjab as it prevents weed growth. Further, coarse textured porous soils with high infiltration rates (Chauhan et al., 2012) combined with high evaporation particularly in arid southern regions (Zone IV & V) requires enormous quantities of water to maintain the water level for submerged paddy. This has led to over-exploitation of groundwater resources (Singh, 2012), apart from a ten-fold increase in emissions due to groundwater pumping from 1980 to 2010 (Benbi, 2018). It is functioning as a positive feedback loop in which free energy (electricity) for irrigation is leading to increased water consumption, followed by declining water tables; which, in turn, is entailing higher energy consumption to pump out water from greater depths. A policy level decision is required to break this loop, and reduce both water and energy consumption. Changing the cropping pattern could be one option, but the minimum support price (MSP) at which the government procures food grains from farmers is a major deciding factor. A shift in farmer's preference from submerged paddy production would require an economic incentive apart from awareness building on the alternative practices. Improving pump set efficiency and irrigation efficiency (Benbi, 2018), use of solar PV (photo-voltaic) water pumps, use of zero-till 'happy-seeder' implement that seeds wheat into fields having rice residue are certain ways of decreasing CF and reducing cost of cultivation. However, the use of solar pumps is hindered by high installation cost, particularly, and free electricity for irrigation (Chandel et al., 2015). Similarly, the happy-seeder technology has a low adaptation rate despite its high cost being subsidized by the government due to reasons cited in Sidhu et al. (2015). Additionally, during the field visits it was found that lack of awareness about the technology was also prevalent among the farmers and acted as a barrier to its adoption. Therefore, the government has a major role to play by diverting power subsidies to incentivize adoption of renewable energy, or technology, along with spreading awareness about the same. This can reduce the GHG emissions and water consumption in agriculture.

4.6. Limitations

The data used for CF assessment was based on farmers' recall of the crops of previous season, and might be subject to recall bias. Zone III might have been subject to bias since most of the survey was done with progressive farmers who practice farming with minimum inputs. This might not be the case with majority of the farmers. Global or default

emission factors (EF) were used for calculation of CF wherever region or country specific EFs were not available (EF for pesticide and seed). Since the data for soil N₂O emissions was not available for each zone, common N₂O EF for Punjab was used for all the zones. In the case of WF assessment, monthly climate data was available for Zone II, while for other zones daily climate data was used. Lastly, the study was limited to water footprint assessment based on CROPWAT estimates. Actual irrigation water use and losses were not accounted for; therefore, there could be a gap between the results of this assessment and actual water footprint.

5. Conclusion

Carbon footprint and water footprint of rice and wheat production was quantified for five agroclimatic zones of Punjab using questionnaire-based survey data. The CF was found to be significantly different among the five zones. Crop residue burning was found to be the principal determinant of variation among zones. Rice production had a higher CF and a wider CF variability across regions as compared to wheat. The semi-arid zones (Zone IV and V) had higher CF for rice and wheat as compared to other zones. Since factors contributing to CF vary regionally, mitigation efforts that consider regional diversity would be more effective than the efforts based on assessments at country level. However, the variation in carbon footprint of agroclimatic zones appears to stem majorly from differences in management practices rather than geoclimatic conditions or resource consumption. More studies should be conducted to understand the factors behind adoption of certain management practices. Since factors like literacy could affect management practices, mitigation efforts should target the root cause, while, encouraging and incentivizing alternative practices. This could be effective in the long run, particularly for developing countries. Nitrogen fertilizer use was found to be the greatest GHG hotspot that should be targeted for mitigation. This would also reduce grey WF which has increased over the years, despite the increase in productivity, due to a surge in fertilizer use.

The green-blue WF of crops in different zones appeared contradictory to climatic conditions, indicating that high annual rainfall does not necessarily make a region better in terms of blue water saving. Further, the energy consumed by groundwater irrigation indicates that there is disparity between the actual water consumption and model-based estimates for blue WF. Therefore, knowledge of actual irrigation water consumption, particularly for flood irrigated crops in water stressed regions is very crucial. Solely using theoretical assessments of WF can lead to wrong conclusions and inappropriate policies. Previous studies have relied on CROPWAT based WF estimates for crop production, and therefore, did not reflect the severity of water usage which was evident in the groundwater levels of Punjab. This study also found that that farm-survey based environmental assessments for crop production can better capture the existing management practices among farmers, and provide accurate inputs for effective policy formulation. Lastly, the government has a major role in reduction of CF and WF by revamping energy policies for optimal use of electricity and incentivizing the use of renewable energy, resource conservation practices and uptake of technology.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Acknowledgement

We thank Punjab Agricultural University, Ludhiana, Punjab and Krishi Vigyan Kendras (extension centers) of Ludhiana, Ballawal, Bhatinda, Fazilka, Ropar for their support in data collection. One of the authors acknowledges the fellowship received from the host institute (NIFTEM). We acknowledge the anonymous reviewers for their valuable inputs.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2020.102959>.

References

- Aggarwal, R., Kaushal, M., Kaur, S., Farmaha, B., 2009. Water resource management for sustainable agriculture in Punjab, India. *Water Sci. Technol.* 60 (11), 2905–2911.
- Ali, S.A., Tedone, L., Verdini, L., Mastro, G.De., 2017. Effect of different crop management systems on rainfed durum wheat greenhouse gas emissions and carbon footprint under Mediterranean conditions. *J. Clean. Prod.* 140, 608–621.
- Arunrat, N., Wang, C., Pumijumnong, N., 2016. Alternative cropping systems for greenhouse gases mitigation in rice field: a case study in Phichit province of Thailand. *J. Clean. Prod.* 133, 218–227.
- Benbi, D.K., 2018. Carbon footprint and agricultural sustainability nexus in an intensively cultivated region of Indo-Gangetic Plains. *Sci. Total Environ.* 644, 611–623.
- BSI and Carbon Trust, 2011. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. pp. 36 Publicly Available Specification-PAS 2050:2011. London, UK.
- Cao, X., Wu, M., Shu, R., Zhuo, L., Chen, D., Shao, G., Guo, X., Wang, W., Tang, S., 2018. Water footprint assessment for crop production based on field measurements: a case study of irrigated paddy rice in East China. *Sci. Total Environ.* 610–611, 84–93.
- CGWB (Central Ground Water Board). 2013. Ground water information booklet Hoshiarpur district, Punjab. Ministry of water resources. Government of India. North western region. Chandigarh. Available at http://cgwb.gov.in/district_profile/punjab/hoshiarpur.pdf (accessed on 1 June 2019).
- CGWB (Central Ground Water Board). 2011. Ropar District Punjab. Ground water information booklet Ropar district, Punjab. Ministry of water resources. Government of India. North western region. Chandigarh. Available at http://cgwb.gov.in/District_Profile/Punjab/Ropar.pdf (accessed on 1 June 2019).
- Chandel, S.S., Naik, M.N., Chandel, R., 2015. Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renew. Sust. Energ. Rev.* 49, 1084–1099.
- Chauhan, B.S., Mahajany, G., Sardanay, V., Timsina, J., Jat, M.L., 2012. Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: problems, opportunities, and strategies. *Adv. Agron.* 117, 315–369.
- ENVIS, 2018. Envis Centre: Punjab. Available at: <http://punenvis.nic.in/index1.aspx?lid=5617&mid=1&langid=1&linkid=1257> (accessed 9 March 2019).
- ENVIS, 2020. Agriculture. Ministry of Environment, Forests & Climate Change, Govt of India. Available at: <http://www.punenvis.nic.in/index1.aspx?lid=5617&mid=1&langid=1&linkid=1257> (accessed 10 July 2020).
- EPA, 2005. List of Drinking Water Contaminants: Ground Water and Drinking Water, US Environmental Protection Agency. Available at: www.epa.gov/safewater/mcl.html#1.
- Ercin, A., Ertug Hoekstra, A.Y., 2012. Carbon and water footprints concepts, methodologies and policy responses. In: United Nations World Water Assessment Programme Side Publications Series. United Nations Educational, Scientific and Cultural Organization, France.
- FAO, 2017. Water for Sustainable Food and Agriculture: A Report Produced for the G20 Presidency of Germany. Food and Agricultural Organization (FAO), Rome Available at: <http://www.fao.org/3/a-i7959e.pdf> (accessed 10 July 2020).
- Ghosh, B., Chakma, N., 2019. Composite indicator of land, water and energy for measuring agricultural sustainability at micro level, Bardhaman District, West Bengal. *India. Ecol. Indic.* 102, 21–32.
- Government of India, 2018. Agricultural Statistics at a Glance. Available at: <https://eands.dacnet.nic.in/> (accessed 5 December 2019).
- Hira, G.S., 2009. Water management in northern states and the food security of India water management in northern states and the food security of India. *J. Crop Improv.* 23 (2), 136–157.
- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.
- IPCC, 2006. IPCC guidelines for national greenhouse gas inventories. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Japan.
- IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Capital dilemma: Growth and inequity in Washington D.C. Cambridge University Press, United Kingdom and New York, NY, USA.

- Johnson, M.D., Rutland, C.T., Richardson, J.W., Joe, L., ... Joe, L., 2016. Greenhouse Gas Emissions from U.S. Grain Farms. *J. Crop Improv.* 30 (4), 447–477.
- Kashyap, D., Agarwal, T., 2020. How reliable are theoretical estimates of water use? A proposed methodology for estimation of actual groundwater consumption in crop production. (Manuscript submitted for publication).
- Kaur, J., Gill, K.K., Kaur, S., Aggarwal, R., 2017. Estimation of crop coefficient for rice and wheat crops at Ludhiana Estimation of crop coefficient for rice and wheat crops at Ludhiana. *J. Agrometeorol.* 19 (2), 170–171.
- Kool, A., Marinussen, M., Blonk, H., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. GHG Emissions of N, P and K fertilizer production. Blonk Consultants (Ed.).
- Linquist, B.A., van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Glob. Chang. Biol.* 18, 194–209.
- Lohan, S.K., Jat, H.S., Yadav, A.K., Sidhu, H.S., Jat, M.L., Choudhary, M., Peter, J.K., Sharma, P.C., 2018. Burning issues of paddy residue management in north-west states of India. *Renew. Sust. Energ. Rev.* 81, 693–706.
- Mekonnen, M.M., Hoekstra, A.Y., 2010. A global and high-resolution assessment of the green, blue and grey water footprint of wheat. *Hydrol. Earth Syst. Sci.* 14 (7), 1259–1276. <https://doi.org/10.5194/hess-14-1259-2010>.
- Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* 15, 1577–1600.
- Page, G., Ridoutt, B., Bellotti, B., 2012. Carbon and water footprint trade-offs in fresh tomato production. *J. Clean. Prod.* 32, 219–226.
- Pathak, H., Jain, N., Bhatia, A., Patel, J., Aggarwal, P.K., 2010. Carbon footprints of Indian food items. *Agric. Ecosyst. Environ.* 139, 66–73.
- Press Information Bureau, Government of India, Ministry of Agriculture & Farmers Welfare, 2019. Categorisation of Farmers. Available at: <https://pib.gov.in/newsite/PrintRelease.aspx?relid=188051> (Accessed 30 April 2019).
- Punjab Agricultural University, 2017. Package of Practices for Crops of Punjab 2017–18. (Ludhiana).
- Sarkar, A., Das, A., 2014. Groundwater Irrigation Electricity –Crop Diversification Nexus in Punjab: Trends, Turning Points and Policy Initiatives, Economic and Political Weekly, Vol XLIX No 52.
- Schafer, F., Blanke, M., 2012. Farming and marketing system affects carbon and water footprint - a case study using Hokaido pumpkin. *J. Clean. Prod.* 28, 113–119.
- Sidhu, H.S., Singh, M., Singh, Y., Blackwell, J., Kumar, S., Humphreys, E., ... Singh, S., 2015. Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research* 184, 201–212.
- Singh, K., 2012. Electricity subsidy in Punjab agriculture: extent and impact. *Indian J. Agric. Econ.* 67, 4.
- Singh, K.B., Jalota, S.K., Sharma, B.D., 2009. Effect of continuous rice–wheat rotation on soil properties from four agro-ecosystems of Indian Punjab. *Commun. Soil Sci. Plant Anal.* 40 (17–18), 2945–2958.
- Smith, P., Bustamante, ... Tubiello, F., 2014. Agriculture, forestry and other land use (AFOLU). In: Edenhofer, O. ... Seyboth, K. (Eds.), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Song, L., Oeurng, C., Hornbuckle, J., 2015. Assessment of Rice Water Requirement by Using CROPWAT Model Assessment of Rice Water Requirement by Using CROPWAT Model, the 15th Science Council of Asia Board Meeting and International Symposium. (Cambodia).
- Sood, A., 2016. 'Growing paddy takes heavy toll on groundwater table'. *The Tribune*. 1/6/2016. Available at: <https://www.tribuneindia.com/news/punjab/community/growing-paddy-takes-heavy-toll-on-groundwater-table/245071.html> (accessed 3 April 2019).
- Statistical Abstract Punjab. 2017. Statistical Abstract Punjab. Economic Advisor to Government of Punjab, Economic and Statistical Organization, Government of Punjab, India. p 29, (Publication No. 956). Available at <https://www.esopb.gov.in/Static/Publications.html> (Accessed 10 July 2019).
- Statistical Abstracts of Punjab, 2019. 2017. Available at: <https://www.esopb.gov.in/Static/Publications.html> (accessed 10 July 2019).
- Tahmasebi, M., Feike, T., Soltani, A., Ramroudi, M., Ha, N., 2018. Trade-off between productivity and environmental sustainability in irrigated vs. rainfed wheat production in Iran. *J. Clean. Prod.* 174, 367–379.
- Thanawong, K., Perret, S.R., Basset-Mens, C., 2014. Eco-efficiency of paddy rice production in Northeastern Thailand: a comparison of rainfed and irrigated cropping systems. *J. Clean. Prod.* 73 (1), 204–217.
- Vetter, S.H., Sapkota, T.B., Hillier, J., Stirling, C.M., Macdiarmid, J.I., Aleksandrowicz, L., ... Smith, P., 2017. Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. *Agric. Ecosyst. Environ.* 237, 234–241.
- Vetter, S.H., Sapkota, T.B., Hillier, J., Stirling, C.M., Macdiarmid, J.I., ... Smith, P., 2019. Corrigendum to Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change. *Agric. Ecosyst. Environ.* 272, 83–85.
- WRI, 2014. 6 Graphs Explain the World's Top 10 Emitters. Available at: <https://www.wri.org/blog/2014/11/6-graphs-explain-world-s-top-10-emitters>.
- WRI, 2019. 17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress. Available at <https://www.wri.org/blog/2019/08/17-countries-home-one-quarter-world-population-face-extremely-high-water-stress> (accessed 16 January 2020).
- Yan, M., Cheng, K., Luo, T., Yan, Y., Pan, G., Rees, R.M., 2015. Carbon footprint of grain crop production in China - based on farm survey data. *J. Clean. Prod.* 104, 130–138.
- Zhang, D., Shen, J., Zhang, F., Li, Y., Zhang, W., 2017. Carbon footprint of grain production in China. *Sci. Rep.* 7, 41261.