Research Article

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Impacts of chemical crop protection applications on related CO_2 emissions and CO_2 assimilation of crops

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Abstract

BACKGROUND: A major global challenge is to provide agricultural production systems that are able to sustain growing demands for food, feed, fibre and renewable raw materials without exacerbating climate change. Detailed and reliable data on the CO_2 balance of different agricultural management activities and inputs as a basis to quantify carbon footprints of agriculture are still lacking. This study aims to fill this gap further by quantifying the net balance of emitted and assimilated CO_2 due to the application of crop protection treatments on the farm, and by assessing their partial contribution to GHG emissions and mitigation in agriculture. The study focuses on key agricultural crops including wheat, corn, oilseeds and sugar crops.

RESULTS: The final CO_2 balance, considering GHG emissions due to on-farm CPP treatment in comparison with CO_2 storage in additional biomass, CO_2 protected with respect to agrotechnical inputs and land inputs and CO_2 saved with respect to associated global land use changes, is positive and may reach multiples of up to nearly 2000.

CONCLUSION: The results highlight the importance of the positive yield effects of the CPP programme applications on the farm, resulting in additional assimilated biomass at the farm level and less land use changes at the global level, and thus lower pressure on environmentally important indicators of overall agricultural sustainability.

Supporting information may be found in the online version of this article.

Keywords: wheat; corn; soybeans; oilseed rape; sugar beets; sugar cane; chemical crop protection; climate change; CO_2 balance; agriculture

1 INTRODUCTION

Climate change is one of the main concerns of modern civilisation, and the impact of human activities on global climate change has become a familiar topic to many people. While most of the increase in greenhouse gas (GHG) concentrations is due to CO_2 emissions from fossil fuels, agriculture globally accounts for 14% of total GHG emissions. However, the share increases to about one-third of the total human-induced GHG emissions if related land use changes such as deforestation and cultivation of savannahs, grassland, etc., are taken into account.[1,2]

There is a great potential for climate change mitigation in agriculture through carbon sequestration into soils and plants. Every tonne of carbon added to and stored in plants or soils removes 3.6 t of CO_2 from the atmosphere.[3] Ruesch and Gibbs[4] highlight that about 500 billion t of carbon is stored in living plants worldwide, i.e. more than 60 times the equivalent of annual anthropogenic GHG emissions to the atmosphere. A large amount of this biomass is produced by agricultural activities.[5] This emphasises the particular role of farming practices in reducing GHG emissions but also at the same time utilising the potential for climate change mitigation through CO_2 assimilation. The global challenge is to provide agricultural production systems that are able to sustain growing demands for food, feed, fibre and agrofuels without exacerbating climate change.

Efficient and effective crop protection plays an important role in tackling this challenge. Crop protection treatments cause direct and indirect GHG emissions but also ensure higher yields and overall biomass production, which results in additional CO_2 assimilation in plants and lower land requirements to meet the demand. This is an essential added value for the society to use the additional assimilated CO_2 for food, feed, fibre and renewable raw materials caused by the application of crop protection products (CPPs).

Sustainable food and farming indicators for the United Kingdom published by Defra[6] show that directly emitted GHGs for using CPP are relatively small compared with other agricultural inputs such as animal feeds, fertilisers and electricity consumption. However, while data on the carbon footprint of producing CPPs (from the cradle to the farm gate) are readily available, an apparent lack of data exists with respect to the carbon footprint of the very partial application of crop protection treatments on the farm.

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The questions arising are as follows: is the net CO_2 balance of crop protection treatments on the farm positive or negative, and can efficient crop protection, besides improving agricultural crop yields, also help to protect the climate? In other words, is a sustainable chemical crop protection on the farm, i.e., in the present analysis, only from the CPP distributor, on the farm and in the field, including harvest, a concrete contribution to climate protection?

Many existing studies have carried out life cycle assessments for various agricultural and food products.[7–12] While these studies provide some valuable insights into the carbon footprint of agriculture, the discussions of sector emissions and mitigation potentials are often rather general and lack details.[13] Few studies pay attention to a specified analysis of the impacts of single agricultural production technologies such as crop protection treatment on the farm upon the CO_2 balance.[14,15] What is missing are detailed and reliable data on the CO_2 balance of different and specific agricultural management practices as a solid basis further to develop quantification of carbon footprints of agriculture.

The present study aims to fill this gap by quantifying the very particular CO_2 balance of a single agricultural production technology, namely CPP programme application by farmers. Therefore, the CO_2 balances for a wide range of applications on different key agricultural crops across different countries are assessed to capture a rather broad spectrum of CPPs and different regional agricultural crop systems. The main subobjectives of the analysis are to quantify the net balance of emitted and assimilated CO_2 due to the application of crop protection treatments on the farm and to assess the overall contribution of crop protection to GHG emissions and mitigation in agriculture. Hence, unlike many other studies, especially life cycle assessments, the study focuses only on one very specific part of a standardised life cycle analysis for agricultural products. Owing to these specific system borders of the present analysis, the study does not include the emitted CO_2 caused by manufacturing CPPs, nor the degradation of the additional biomass produced. Rather, it expands on the details of the particular analysis and includes all major aspects from distributor via the farm gate to the harvesting of the crop. The study focuses on key agricultural crops including wheat, corn, soybeans, oilseed rape, sugar beets and sugar cane.

The paper is structured as follows. Section 2 will briefly outline the developed and applied methodology. This is followed by a detailed presentation of the results for the different CPP applications for wheat, corn, oilseeds and sugar crops in Section 3. Section 4 discusses the results in the context of findings from other studies, the role of crop protection for GHG emissions and mitigation and wider policy issues.

2 METHOD

Calculating the CO_2 balance of on-farm application of CPPs in agricultural production systems requires a methodological approach that can separately analyse the various climate change impacts of the relevant input and output factors and finally compute the aggregated CO_2 balance(s) resulting from the comparison of the various input and output impacts. By doing so, the calculations have to cover not only CO_2 but also emissions and absorptions of methane and nitrous oxide, which are transformed into equivalents of carbon dioxide [CO_2 (-eq.)]. In addition, the methodological framework needs to take into account that a CPP treatment (or the removal of the treatment) influences land use changes. The methodological framework developed in this study particularly accounts for such interregional market interdependencies and quantifies resulting changes in crop production and land allocations in other countries and regions, which impact in the long-run upon the CO_2 balance of CPP applications (see Section 4, balance IV). CO_2 balances have not been measured, but are calculated by using well-accepted literature findings on specific emissions, carbon contents, etc., and are expressed in multiples calculated as the ratio of the respective CO_2 assimilation, etc., divided by CO_2 emission due to CPP treatment, all in kg CO_2 (-eq.) ha^{-1}. Altogether, a stepwise approach is applied, which can be described as follows.

In the first step, CO_2 (-eq.) emitted due to the treatment with CPPs on the farm is calculated. This sets the basis for the entire balancing and includes emissions mainly due to energy consumption of different pre-field, on-field and post-field activities, such as the purchase of CPPs from a distributor and the associated transport to the farm, the mixing and application of CPPs, the use of seed treaters, if applicable, tractors and additional spraying equipment, the monitoring of the need of CPP applications and their impacts on the field and the transport, handling and waste treatment of empty CPP containers (e.g. burning versus recycling).

Starting with the calculation of the CO_2 (-eq.) emissions of different pre-field, on-field and post-field activities related to direct CPP application on the farm, diesel and energy consumptions need to be converted to CO_2 (-eq.). Rothe[16] provides a conversion factor for diesel, while kWh (MJ) consumption was converted following country-specific conversion factors provided by IFEU.[17]

The CO_2 (-eq.) emission rate caused by manufacturing, formulating and packaging of CPPs, as well as global transportation, is not included, because respective data for all analysed products used in this study are not available. Hitherto, analysed CPPs have shown a range of 2–10 kg CO_2 (-eq.) emissions per manufactured, formulated and packaged kilogram of CPP (Bayer Technology Services, unpublished). This suggests that respective CO_2 (-eq.) emission rates per hectare are of little relevance.

While most of the required data were obtained through specifically designed expert surveys done by Bayer CropScience experts (see the supporting information 'Questionnaire'), some missing and questionable information had to be collected through a literature review.[18–22]

The second step quantifies the CO_2 (-eq.) assimilated in additional biomass grown owing to the treatment with a CPP programme. Crop protection treatments lead to supplementary yield as well as 'non-yield' organs, and thereby dry matter biomass production, which accounts for additionally assimilated CO_2. Yield differences occurring by comparing crops with and without CPP treatment have been provided by expert knowledge and determine this additionally assimilated CO_2. The dry matter and carbon content of the supplementary crop yield, as well as the 'non-yield' biomass production, has been quantified using data from Bakker, Ecoinvent,[20] KTBL,[21,22] Bakker,[23] Rathke *et al.*,[24] USDA[25] and van Dam *et al.*,[26] to determine the carbon included in additionally formed dry matter from yield and 'non-yield' parts of the crop. The additionally stored carbon is then converted into CO_2 (-eq.) assimilated in additional biomass use.[27–29] A first balance of CO_2 emitted owing to a CPP treatment in comparison with CO_2 assimilated in additional biomass can thus be calculated:

$$\text{Balance I} = CO_2\ (\text{- eq.})_{AA} / CO_2\ (\text{- eq.})_{DE} \qquad (1)$$

with CO_2 (-eq.)$_{AA}$ – CO_2 (-eq.) assimilated in additional biomass, and CO_2 (-eq.)$_{DE}$ – CO_2 (-eq.) directly emitted owing to the CPP treatment.

The third step calculates CO_2 (-eq.) emissions from other technical inputs of the crop production systems (e.g. diesel/energy used to plough, to saw, to fertilise, to irrigate and to harvest) that would be partly or fully wasted in the case of lower yields or full damage occurring when a CPP treatment is not applied. In other words, the necessary emissions caused by these technical inputs are specifically protected by the treatment with a CPP programme. The same data sources as in the first step are used to calculate the saved emissions, but also additional sources were taken into account.[20–22,30] A more detailed balance of CO_2 emitted owing to a CPP treatment in comparison with CO_2 assimilated in additional biomass plus CO_2 protected with respect to technical inputs can then be calculated:

$$\text{Balance II} = [CO_2\text{ (- eq.)}_{AA} + CO_2\text{ (- eq.)}_{ST}]/CO_2\text{ (- eq.)}_{DE} \quad (2)$$

with CO_2 (-eq.)$_{ST}$ – CO_2 (-eq.) emissions protected with respect to technical inputs.

The fourth step additionally takes into account the fact that the treatment of crops with CPP saves emissions associated with the use of agriculturally employed soil, i.e. methane and nitrous oxide soil emissions occurring while using cultivated land. It does not include the emissions caused by the production and application of fertiliser, which is already addressed in balance II. Data were calculated on the basis of a comprehensive literature review.[7,20,31] A third CO_2 balance can be calculated:

$$\text{Balance III} = [CO_2\text{ (- eq.)}_{AA} + CO_2\text{ (- eq.)}_{ST} + CO_2\text{ (- eq.)}_{SI}]/CO_2\text{ (- eq.)}_{DE} \quad (3)$$

with CO_2 (-eq.)$_{SI}$ – CO_2 (-eq.) emissions saved with respect to land inputs.

The removal of CPP programmes would cause land use changes because lower yields affect the comparative advantages and disadvantages of farmers, resulting in alternative cropping decisions, which will, over time, cause land use changes and finally climate change worldwide.[2] Respective emissions are incorporated into the CO_2 (-eq.) balancing by applying a fifth and final step.

A farmer faced with a lower yield owing to the removal of a CPP treatment may cultivate additional land to compensate for the production loss occurring on one hectare of cropland. CO_2 that is sequestered in plant biomass and in the soil not yet ploughed will be released to the air in the short run and in a regional context. On the other hand, it is not only the farmer facing yield losses who compensates for production shortages, but farmers with a comparative advantage in other regions will close the existing (world market) gap. This implies an indirect land use change, especially with respect to non-cultivated land, e.g. tropical rain forests.

Such agricultural land use changes depend on the decisions of farmers to modify their crop production in response to market and price changes worldwide. In order to account for such a realistic outcome, a multiregion, multimarket (partial) equilibrium model (MMM) was developed, based on Jechlitschka *et al.*,[32] and incorporated into the methodological framework of the study. Such an MMM approach, which links regions and markets interactively, is widely used in the economic analysis of agricultural change. MMMs are particularly suitable for the simulation of alternative production scenarios and quantify in a rather detailed way changes in agricultural production.[33,34] This may be linked to land use changes for the production of various goods (see supporting information 'MMM').[35]

Further evidence concerning the carbon sequestered in soils that may additionally be brought into cultivation in the absence of CPP treatment makes it possible to determine the final CO_2 (-eq.) balance. Searchinger *et al.*[36] and Searchinger and Heimlich[37] provide a database on historical land use changes and associated carbon stock changes caused by arable production for selected countries and all continents. The necessary additional data were used in balance IV:

$$\text{Balance IV} = [CO_2\text{ (- eq.)}_{AA} + CO_2\text{ (- eq.)}_{ST} + CO_2\text{ (- eq.)}_{SI} + CO_2\text{ (- eq.)}_{LC}]/CO_2\text{ (- eq.)}_{DE} \quad (4)$$

with CO_2 (-eq.)$_{LC}$ – CO_2 (-eq.) emissions saved from land use changes.

3 RESULTS

The study aims to cover a wide range of different CPP treatments applied to various crops in selected countries. This paper presents the results of ten wheat, five corn, ten oilseed and five sugar crop CPP treatments. Respective results for potatoes, bananas, carrots, cotton, jatropha, tomatoes and grapes are not included here, but are presented by Kern.[38]

Table 1 provides an overview of the composition and concentration of the different CPP programmes, highlighting that in many cases the selected treatments did not consist of one crop protection product but a combination of different treatments.

Taking the CPP application of Fandango® in wheat in Germany as an example, Fig. 1 accordingly depicts the direct CO_2 (-eq.) emission due to the CPP application and the contribution of the various related activities. It shows that in this example more than 10 kg of CO_2 (-eq.) is emitted owing to the application of the CPP programme. Direct application of CPP and transport of bins from farm to waste treatment facilities contributed the largest share, while the waste treatment is a rather minor factor and seed treatment does not count at all here.

Taking the CPP application of Nativo® in soybeans in Brazil as another example, Fig. 2 depicts the direct CO_2 (-eq.) emission due to CPP application and the contribution of the various related activities. Figure 2 shows that in this example more than 15 kg of CO_2 (-eq.) is emitted owing to the application of the CPP programme. Direct application of CPP contributed the largest share here, followed by indirect energy use and transport of bins from farm to waste treatment facilities. Monitoring of pests and diseases by car or tractor and also waste treatment are rather minor factors.

The CO_2 (-eq.) emissions of the Fandango® application in wheat in Germany and the Nativo® application in soybeans in Brazil are at the lower end in comparison with the other analysed CPP programmes; in particular, treatment programmes that combine several CPPs result in higher CO_2 (-eq.) emissions. Column H of Tables 2a and b compares the total CO_2 (-eq.) emitted owing to the treatment with CPP programmes as described in Table 1. Altogether, CO_2 (-eq.) emissions range from 5.7 to 34.5 kg ha^{-1}. Different numbers of CPPs and varying product concentrations in the applications (see Table 1 again) lead to large variations in the CO_2 (-eq.) emissions. Tables 2a and b (column C) also show that CO_2 (-eq.) emissions are largely influenced by the number

Table 1. Overview of analysed CPP programmes of wheat, corn, oilseeds and sugar crops

No.	Crop	Country	CPP and concentration
1	Wheat	Argentina	Scenic® 0.15 L ha^{-1}, Husar OD® 0.28 L ha^{-1}, Sphere® 0.70 L ha^{-1}
2	Wheat	Australia	Atlantis® 0.33 L ha^{-1}
3	Wheat	France	Archipel®/Aloes® 0.21 L ha^{-1}, Atlantis®/Absolu® 0.33 L ha^{-1}, Fandango S® 1.25 L ha^{-1}, Decis Protech® 0.38 L ha^{-1}, Mesurol Pro® 2.40 L ha^{-1}, Gaucho Ble®/Ferial Ble® 0.44 L ha^{-1}
4	Wheat	Germany	Fandango® 1.50 L ha^{-1}
5	Wheat	South Africa	Cossack® 0.30 g ha^{-1}, Prosaro® 0.40 L ha^{-1}, Folicur Plus® 0.60 L ha^{-1}
6	Wheat	South Africa	Folicur® 0.75 L ha^{-1}
7	Wheat	Turkey	Sportak® 1.00 L ha^{-1}, Prosper Combi® 0.60 L ha^{-1}, Flamenco® 1.00 L ha^{-1}
8	Wheat	UK	Proline® 0.60 L ha^{-1}, Chlorothalonil® 1.00 L ha^{-1}, Firefly® 2.50 L ha^{-1}
9	Wheat	USA	Stratego® 0.88 L ha^{-1}
10	Wheat	USA	Wolverine® 1.66 L ha^{-1} or Olympus® 0.20 L ha^{-1}
11	Corn	Brazil	CropStar® 0.30 L ha^{-1}, Connect® 0.75 L ha^{-1}, Soberan® 0.25 L ha^{-1}, Nativo® 0.60 L ha^{-1}, Certero® 0.10 L ha^{-1}, Larvin® 0.20 L ha^{-1}
12	Corn	France	Mikado® 0.53 L ha^{-1}, Decis Protech® 0.80 L ha^{-1}
13	Corn	Germany	Laudis® 2.00 L ha^{-1}
14	Corn	USA	Corvus® 0.41 L ha^{-1}
15	Corn	USA	Stratego® 0.75 L ha^{-1}
16	Soybeans	Argentina	Imidacloprid® and Beta (Connect)® 750 cm^3 ha^{-1}, Sphere Max® 150 cm^3 ha^{-1}
17	Soybeans	Brazil	Nativo® 1.5 L ha^{-1}
18	Soybeans	Brazil	Nativo® 1 L ha^{-1}
19	Soybeans	Brazil	Nativo® 0.6 L ha^{-1}, Aureo® 0.6 L ha^{-1}
20	Soybeans	Brazil	Glyphosate® 1 L ha^{-1}, Atento® 3 L t^{-1}, CropStar® 3 L t^{-1}, Certero® 0.05 L ha^{-1}, Belt® 0.04 L ha^{-1}, Connect® 0.75 L ha^{-1}, Tamaron® 0.6 L ha^{-1}, Nativo® 0.5 L ha^{-1}
21	Soybeans	USA	Stratego YLD® 0.29 L ha^{-1}, Leverage 360® 0.21 L ha^{-1}
22	Oilseed rape	Canada	Prosper FX® 0.08 L ha^{-1}, Liberty® 3.22 L ha^{-1}, Centurion® 0.1 L ha^{-1}, Proline® 0.32 L ha^{-1}
23	Oilseed rape	France	Horizon® 0.62 L ha^{-1}, Joao® 0.44 L ha^{-1}, Decis Protech® 0.32 L ha^{-1}, Decis Expert® 0.05 L ha^{-1}, Mesurol® 2.5 L ha^{-1}
24	Oilseed rape	Germany	Brasan® 2 L ha^{-1}, Folicur® 1.5 L ha^{-1}, Proline® 0.42 L ha^{-1}, Decis fl.® 0.24 L ha^{-1}, Biscaya® 0.33 L ha^{-1}, Elado® 0.12 L ha^{-1}
25	Oilseed rape	UK	Chinook® 0.1 L ha^{-1}, Modesto® 0.08 L ha^{-1}, Proline® 1.3 L ha^{-1}
26	Sugar beets	France	Bethanal Booster® 0.80 L ha^{-1}, Sphere® 0.6 L ha^{-1}, Decis Protech® 0.42 L ha^{-1}, Imprimo® 0.23 L unit^{-1}
27	Sugar beets	Germany	Sphere® 0.9 L ha^{-1}
28	Sugar beets	Germany	Betanal Expert® 3.3 L ha^{-1}, Targa Super® 0.3 L ha^{-1}
29	Sugar beets	UK	Betanal Expert® 3.5 L ha^{-1}, Goltix® 1.75 L ha^{-1}, Venzar® 0.4 L ha^{-1}
30	Sugar cane	Brazil	Provence® 0.17 g ha^{-1}

Source: authors' own table based on Bayer CropScience expert information.

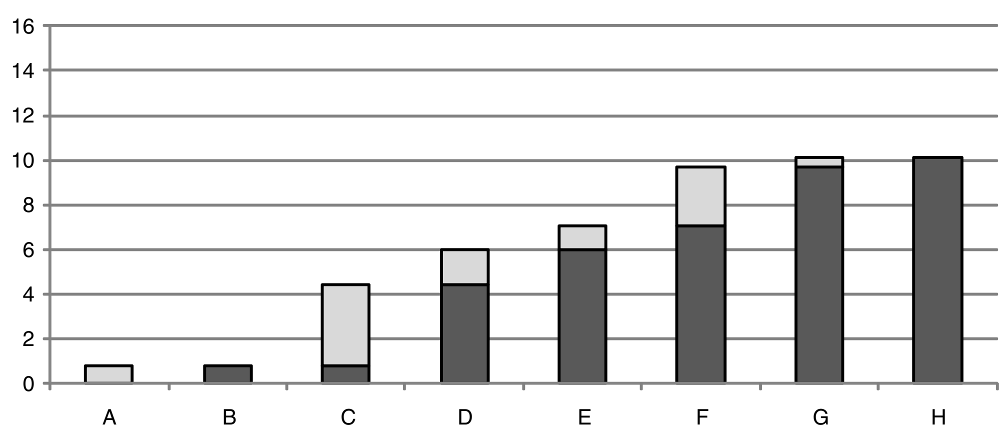

Figure 1. CO_2 emissions of energy amounts consumed while applying Fandango® in wheat in Germany (CPP programme no. 4) [in kg CO_2 (-eq.) ha^{-1}]. A – transport from distributor to farm; B – seed treatment; C – direct application of CPP; D – indirect energy use while applying CPP (cleaning, etc.); E – monitoring; F – transport from farm to waste treatment facility; G – waste treatment; H – total CO_2 equivalents emitted. Light-grey colour symbolises the amount of CO_2 (-eq.) emissions additionally included in the stepwise approach applied; dark-grey colour represents the total amount of CO_2 (-eq.) included after each step. Source: authors' own calculations.

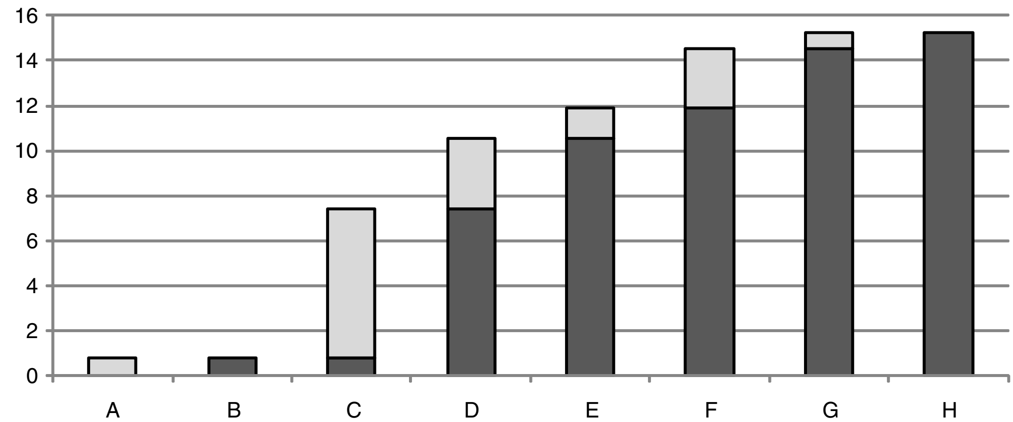

Figure 2. CO_2 emissions of energy amounts consumed while applying Nativo® in soybeans in Brazil (CPP programme no. 18) [in kg CO_2 (-eq.) ha^{-1}]. A – transport from distributor to farm; B – seed treatment; C – direct application of CPP; D – indirect energy use while applying CPP (cleaning, etc.); E – monitoring; F – transport from farm to waste treatment facility; G – waste treatment; H – total CO_2 equivalents emitted. Light-grey colour symbolises the amount of CO_2 (-eq.) emissions additionally included in the stepwise approach applied; dark-grey colour represents the total amount of CO_2 (-eq.) included after each step. Source: authors' own calculations.

of CPP applications and related diesel consumptions. Cases of oilseed treatments with CPPs in France, Germany and the United Kingdom show relatively high CO_2 (-eq.) emissions.

The CO_2 emissions due to CPP programme treatment need to be compared with its CO_2 assimilation impact. Figure 3 compares the CO_2 emissions due to the CPP programme (see column H in Tables 2a and b) with different CO_2 assimilation/emission balances (I to IV), expressed in multiples again, for the example of the Fandango® application in wheat in Germany, and Fig. 4 does so for the Nativo® application in soybeans in Brazil.

The CO_2 balances resulting from all CPP applications analysed are positive. Particularly evident is the positive impact of the additionally formed dry matter from yield and non-yield parts of the crops. Hence, the calculated basic balance I (comparing the CO_2 emissions due to CPP treatment with the CO_2 sequestrated in additionally produced biomass) yields a multiple of around 394 for the wheat example and of nearly 700 in the soybean case. The inclusion of emissions from technical inputs, i.e. diesel and energy supplemented to the agricultural system during the growing season, does not change the multiples a great deal. The reason for balance II being 'only' a little higher than balance I in the wheat example and in the soybean case is that additionally protected emissions from the application of technical inputs other than CPP-related inputs are rather small compared with the CO_2 assimilated in additional biomass caused by CPP. The situation may become more accentuated once methane and nitrous oxide emissions from already cultivated land are taken into account as well. In the wheat example, balance III has a value of 633, almost 240 multiples higher than balance I and still 180 multiples higher than balance II, reflecting the obvious fact that other GHGs count a lot in wheat production at least. Taking into account land use change effects responding to unsatisfied demand, balance IV increases further to 1079 multiples in the wheat example and to more than 2200 multiples in the soybean case. Hence, an impressive, if not the greatest, positive impact on the CO_2 balance can be attributed to land use change effects.

Table 2a for wheat and corn examples and Table 2b for the other cases covered by this paper show in columns I to IV similar relationships between CO_2 emission and CO_2 assimilation to the selected examples above. Just the calculations of the basic balance I (column I) give multiples of between 80 and 781. Only one CPP programme (the application of Cossack®, Prosaro® and Folicur Plus® in wheat in South Africa) has a multiple of less than 100. Such low multiples are usually the case when high application rates coincide with low yield differences and low yield in general. On the other hand, very high multiples are (almost always) associated with only a single or a few applications of CPP using comparatively low diesel or other energy inputs while assuring a high yield difference between the treated and untreated CPP management practice.

As with the example of the Fandango® application on wheat in Germany in Fig. 3, the inclusion of emissions from technical inputs in balance II only increases the multiples to a small extent. For example, multiples only increase by 3% for the CPP programme application in wheat in the United Kingdom (no. 8) and by 4% for the CPP programme application in corn in Brazil (no. 11).

Taking into account saved emissions from soil inputs in balance III, multiples rise between 9 and 90% compared with balance II. This suggests a relatively high importance of soil-based emissions compared with technical emissions.

As outlined above, the consideration of land use changes leads to balance IV. Land use changes have the most dominant effects on the CO_2 balances of CPP programmes, increasing multiples in comparison with balance III by between 46 and 282%. This leads to multiples of between 398 and 1946 for wheat and corn and of 355 and 3609 for oilseeds and sugar crops, taking into account that CPP programmes will be applied over 30 years, thus accumulating emissions from the treatment over time.

Overall, the results show that the CO_2 assimilation substantially outweighs the emissions due to CPP programmes.

4 DISCUSSION

The aim of the analysis was to quantify the net balance of emitted and assimilated CO_2 due to the application of crop protection treatments on the farm, and to assess the overall contribution of crop protection to GHG emissions and mitigation in agriculture. A complex methodological framework was developed and used to calculate CO_2 balances, based on well-accepted literature findings of ten wheat, five corn, ten oilseed and five sugar crop CPP programme applications that take into account the various CO_2 emission and assimilation impacts of the relevant input and output factors and of land use changes at the local and international

Table 2a. CO_2 equivalents emitted (A to H) and CO_2 balances (I to IV) of CPP programme application on wheat and corn

			CO_2 emissions due to CPP programme application [kg CO_2 (-eq.) ha^{-1}]								CO_2 balances: assimilation/ emission (multiples)			
No.	Crop	Country	A	B	C	D	E	F	G	H	I	II	III	IV
1	Wheat	Argentina	0.92	0.11	6.61	3.28	0.66	0.92	1.58	14.08	175	201	297	581
2	Wheat	Australia	0.35	0.00	3.96	1.58	0.88	5.28	0.4	12.46	283	315	380	1235
3	Wheat	France	0.53	0.02	12.68	6.57	1.06	1.06	1.76	23.67	325	339	438	955
4	Wheat	Germany	0.79	0.00	3.65	1.58	1.06	2.64	0.4	10.11	394	453	633	1079
5	Wheat	South Africa	0.26	0.00	2.30	1.58	0.79	0.13	0.6	5.66	80	101	182	398
6	Wheat	South Africa	0.26	0.00	6.90	4.73	0.79	0.13	1.8	14.61	275	333	559	1145
7	Wheat	Turkey	0.26	0.00	10.30	4.73	1.72	0.13	1.8	18.94	436	464	531	1436
8	Wheat	UK	1.45	0.00	15.85	4.73	0.53	1.32	1.2	25.08	529	546	621	1136
9	Wheat	USA	0.79	0.00	4.23	1.58	1.98	4.23	0.55	13.35	120	144	206	487
10	Wheat	USA	0.79	0.00	4.23	1.58	1.98	4.23	0.55	13.35	165	189	250	710
11	Corn	Brazil	0.26	0.01	19.82	8.01	1.98	2.64	2.1	34.82	177	184	216	484
12	Corn	France	0.53	0.00	11.89	4.73	0.79	1.06	1.06	20.05	484	508	589	1178
13	Corn	Germany	0.79	0.00	5.44	1.58	0.79	2.64	0.4	11.65	208	390	527	770
14	Corn	USA	0.66	0.00	14.82	3.15	2.38	1.72	0.9	23.63	779	911	993	1946
15	Corn	USA	0.66	0.00	7.41	1.58	2.38	1.72	0.45	14.19	128	306	417	535

[a] A – transport from distributor to farm; B – seed treatment; C – direct application of CPP; D – indirect energy use (cleaning, etc.); E – monitoring; F – transport from farm to waste treatment; G – waste treatment; H – total CO2 equivalents emitted; I – balance I; II – balance II; III – balance III; IV – balance IV.
Source: authors' own calculations.

Table 2b. CO_2 equivalents emitted (A to H) and CO_2 balances (I to IV) of CPP programme application on oilseeds and sugar crops

			CO_2 emissions due to CPP programme application [kg CO_2 (-eq.) ha^{-1}]								CO_2 balances: assimilation/ emission (multiples)			
No.	Crop	Country	A	B	C	D	E	F	G	H	I	II	III	IV
16	Soybeans	Argentina	0.53	0.00	6.61	3.15	1.85	0.92	1.05	14.11	128	138	226	387
17	Soybeans	Brazil	0.53	0.00	9.91	4.73	1.06	2.64	1.05	19.91	266	271	319	779
18	Soybeans	Brazil	0.79	0.00	6.61	3.15	1.32	2.64	0.50	15.21	683	690	762	2274
19	Soybeans	Brazil	0.53	0.00	6.61	3.15	1.32	2.64	0.70	14.95	450	455	504	1867
20	Soybeans	Brazil	0.53	0.01	16.51	8.01	1.85	2.64	2.10	31.65	358	361	393	1501
21	Soybeans	USA	0.66	0.00	7.41	1.58	2.38	1.72	0.45	14.19	115	125	238	355
22	Oilseed rape	Canada	1.32	0.01	5.49	3.28	0.26	2.64	1.23	14.23	781	835	1018	3609
23	Oilseed rape	France	0.26	0.00	15.85	7.88	2.38	0.88	2.00	29.25	320	332	450	1254
24	Oilseed rape	Germany	0.79	0.01	15.85	6.57	1.59	2.64	2.00	29.44	350	373	499	1346
25	Oilseed rape	UK	1.32	0.01	16.06	6.43	1.59	0.79	1.75	27.95	371	396	463	1596
26	Sugar beets	France	0.53	0.01	15.85	8.14	1.32	0.88	2.12	28.84	261	285	364	670
27	Sugar beets	Germany	1.59	0.00	3.22	1.58	1.32	2.64	0.40	10.75	600	683	930	1434
28	Sugar beets	Germany	1.59	0.00	9.67	4.73	1.32	2.64	1.20	21.14	455	489	590	1166
29	Sugar beets	UK	1.45	0.00	15.85	4.73	0.66	1.32	1.20	25.21	410	442	537	1012
30	Sugar cane	Brazil	0.44	0.00	14.00	1.58	0.88	1.76	0.40	19.06	359	364	406	740

A – transport from distributor to farm; B – seed treatment; C – direct application of CPP; D – indirect energy use (cleaning, etc.); E – monitoring; F – transport from farm to waste treatment; G – waste treatment; H – total CO2 equivalents emitted; I – balance I; II – balance II; III – balance III; IV – balance IV.
Source: authors' own calculations.

level. The results of this paper show that the net CO_2 balance of crop protection treatments of the investigated crops in various countries is very positive, although large variations between the various crop–country–CPP treatments exist owing to different CPP combinations and different growing and climatic conditions.

Just the CO_2 assimilation due to the additionally assimilated biomass is already substantially larger than the CO_2 emissions from the CPP treatment in all analysed crop scenarios. Of the different CO_2 assimilation aspects, land use changes and saved land inputs have the biggest positive impact on the CO_2 balance. On the other hand, CO_2 savings from technical inputs have only a minor impact on the overall CO_2 balance. The results highlight the importance of the positive yield effects of the CPP programme treatments, which lead to additional assimilated biomass and less land use changes at the global level, and thus lower pressure on environmentally important land use systems.

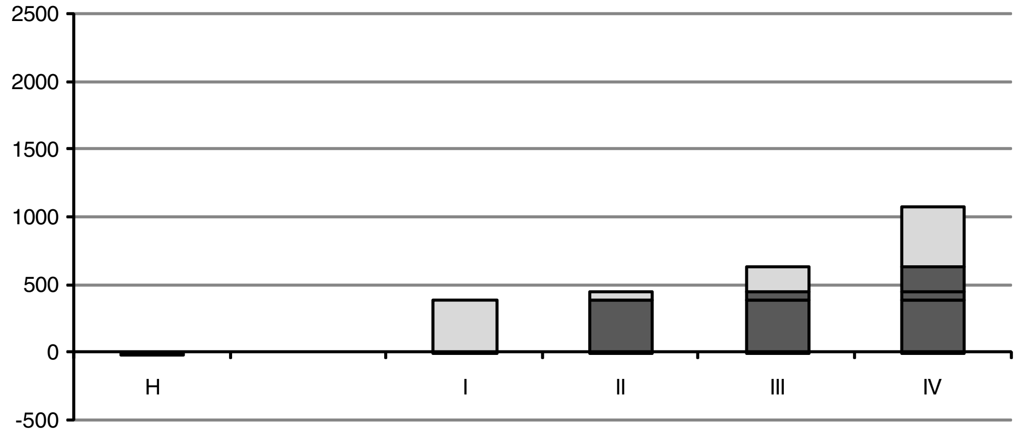

Figure 3. CO_2 assimilation/emission balances for the application of Fandango® in wheat in Germany (CPP programme no. 4) (in multiples). I – balance I; II – balance II; III – balance III; IV – balance IV. Light-grey colour symbolises the amount of CO_2 (-eq.) assimilations/emissions additionally included in the stepwise approach applied; dark-grey colour represents the total amount of CO_2 (-eq.) included after each step. Source: authors' own calculations.

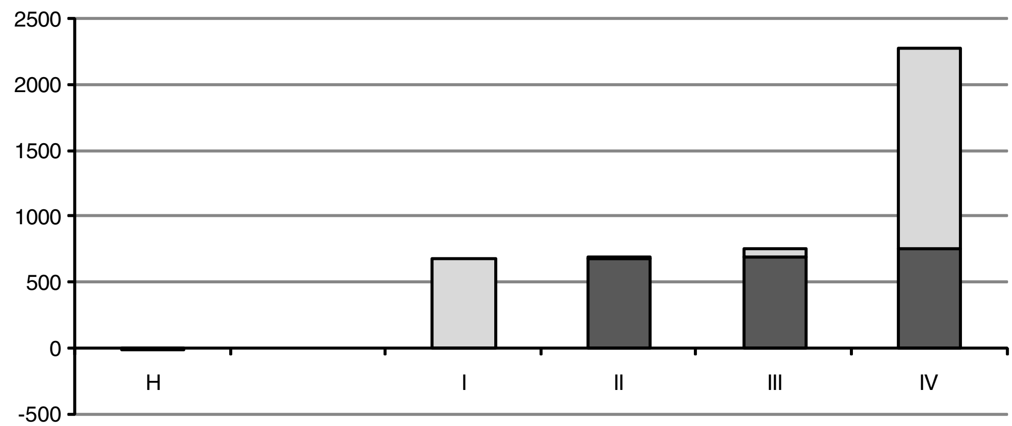

Figure 4. CO_2 assimilation/emission balances for the application of Nativo® in soybeans in Brazil (CPP programme no. 18) (in multiples). I – balance I; II – balance II; III – balance III; IV – balance IV. Light-grey colour symbolises the amount of CO_2 (-eq.) assimilations/emissions additionally included in the stepwise approach applied; dark-grey colour represents the total amount of CO_2 (-eq.) included after each step. Source: authors' own calculations.

The large variations between the various crop–country–CPP treatments can be partly explained by the different CPP compositions and concentrations of the treatment programmes. In addition, differences result from growing and climatic conditions, which have not been considered in the analysis. However, this study does not aim to compare CO_2 assimilations and emissions across different CPP programme treatments, but rather to assess the CO_2 balance of a single agricultural production technology, namely CPP application on the farm. Irrespective of the influence of other factors, such as growing and climatic conditions, on the CO_2 balance, the positive CO_2 balance of CPP programme treatments remains robust.

Some studies have estimated GHG emissions due to the application of CPP and highlighted the relatively high contribution of pesticide applications to GHG emission of agricultural production systems.[39–41] However, the results of the present study show that CO_2 assimilation is substantially higher than the volume of CO_2 and other GHGs emitted when applying a CPP programme. In other words, the results of this study provide a clear indication that the carbon footprint of applying CPPs (from 'farm' gate to grave) is very positive, outweighing the comparatively small CO_2 emission rate of using CPPs (from cradle to farm gate), and is leading to a positive overall carbon footprint for the production and application of CPPs.[38]

Against this background, it has to be noted that the use of data of Searchinger *et al.*[36] and Searchinger and Heimlich[37] on historical land use changes and associated carbon stock changes is crucial for the determination of the present results.[36,37] There is room for debate if the respective carbon values are too high; Tyner *et al.*,[42] for instance, use slightly lower carbon sequestration values. In spite of this, the general finding of the present analysis, i.e. that carbon savings are much higher than carbon emissions caused by the application of CPP programmes on the farm, will not be altered at all.

The following conclusions can be drawn. The positive CO_2 balance indicates that an efficient and effective crop protection not only increases agricultural crop yields but can also play an important role in contributing to the reduction of negative climate impacts of agricultural land use change. In addition, given the expected long-term increase in demand for food, feed, fibre and renewable raw materials over the next decades, potentially lower yields due to a removal of CPP programmes from crop production systems would increase the risk of future food crises and increase the pressure on further land conversion to agricultural land, with negative environmental consequences for biodiversity and climate protection. The realisation of local, regional and global agricultural production potential depends on making productive technologies such as chemical crop protection and synthetic fertiliser and modern seed varieties available to farmers.[43] The results underline the fact that the integration of CPP programmes in sustainable farming frameworks and guidelines helps to develop agricultural production systems that are able to sustain growing demands for food, feed, fibre and renewable raw materials without exacerbating climate change. However, further analyses of agricultural management activities and production technologies are needed reliably to quantify carbon footprints of agriculture.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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