How greenhouse gas emissions relate to crop yields and inputs

Daniel Kindred, Roger Sylvester-Bradley, Christina Baxter, Toby Townsend, Rachel Thorman

Email: Daniel.kindred@adas.co.uk

Key Points:

- Our global population is growing, and we must grow enough to eat. But how can we best avoid associated global warming? Grow intensively, or sparingly?
- We show how practical conclusions from alternative approaches to carbon accounting differ hugely, depending on their assumptions.
- The inclusion of indirect land use change (ILUC) assumptions in our calculations showed carbon intensity minimised with only 4% less grain yield, and was insensitive to fertiliser N.
- The practical application of this will come through sharing and debating the whole endeavor, facilitated by a new network: YEN-Zero.

Introduction

Most people, even farmers, believe that high crop yields need lots of fertiliser and other inputs which worsen the environmental impacts of farming. After looking at this during the biofuels debate in 2008 we in ADAS were not so sure (Kindred et al., 2008; Berry et al.,2010). As climate change and the NFU's commitment to Net-Zero (NFU, 2019) has soared up the farming consciousness over the past couple of years, once again the relationship between inputs and yields, as well as how that relationship is balanced with the overall environmental impacts of crop production, are at the forefront of thinking.

The Morley Agricultural Foundation recently funded us to explore the evidence for these relationships with respect to greenhouse gases (GHG). We used a new dataset created by entries in crop yield competitions organised by the Yield Enhancement Network (YEN) since 2013. This analysis provides a foundation stone for our new 'YEN-Zero' network which aims to provide a community space to share ideas and experiences, to benchmark GHG emissions, and to energise progress in farming towards Net Zero.

Emission sources in cropping

The direct GHG emissions associated with cropping that are counted in the UK's National GHG Inventory are mostly related to the emissions of nitrous oxide (N_2O) from the soil. These are calculated in relation to quantities of nitrogenous materials (manures, fertilisers, crop residues and composts) applied to the soil. Whilst emissions of N_2O typically account for less than 5 kg N/ha (so are unimportant agronomically), the Global Warming Potential of N_2O is huge – around 265-298 times that of CO_2 – so N_2O typically accounts for between 0.6 to 1.5 t CO_2e/ha for grain crops. Emissions from use of diesel fuel for farm machinery do not contribute to agriculture emissions under the GHG inventory when reporting internationally; however, when reporting nationally these emissions are allocated to agriculture. Although this dual approach to reporting may be confusing, it should be noted that these emissions typically amount to less than 0.4 t CO_2e/ha for combinable crops. There are also direct CO_2 emissions associated with applications of lime and urea (~0.2 t CO_2e/ha each), as well as methane emissions from manures and composts.

The emissions associated with the manufacture of agrochemicals and fertilizers are not counted under agriculture emissions; rather, these come under emissions from manufacturing industry, and if manufactured abroad they won't count in the UK National Inventory at all. However, in calculating the carbon footprint or GHG intensity of crops, or their downstream products, including these 'embedded' emissions is important in capturing the overall impact of cropping on climate change.

By far the largest of these embedded emissions is from the manufacture of nitrogen (N) fertilizer; the fixing of N to ammonia from the atmosphere in the Haber-Bosch process is very energy intensive, using large quantities of natural gas as a hydrogen source. In addition, the creation of nitric acid in the production of ammonium nitrate (AN) used to be associated with large on-site emissions of N_2O. However, there is good news here – the fertilizer industry in the UK and Europe has invested very heavily over the past 10 years in technologies to abate these N_2O emissions, so that, where the GHG cost of fertiliser manufacture used to be more than 7 kg CO_2e/ kg N (for AN) it has been halved to around 3.5 kg CO_2e/ kg N now. Many fertiliser manufacturers can now provide accredited GHG intensities for their products or using a carbon calculator developed by Fertilizers Europe (2021). For a typical grain crop the GHG costs associated with N manufacture are around 0.7 t CO_2e/ha. The GHG costs of P & K fertilisers is much less (<0.1 t CO_2e/ha) and the embedded costs of agrochemicals are almost insignificant (total <0.05 t CO_2e/ha). Overall, the total emissions from a typical cereal crop are around 3 t CO_2e/ha.

Carbon sequestration

Whilst agriculture is responsible for around 10% of the UKs GHG emissions it is also the only industry whose primary function is to remove carbon dioxide from the atmosphere, through photosynthesis, to produce energy rich products. Agriculture can therefore not only reach Net-Zero emissions, but uniquely, it has the potential to go net-negative!

A typical crop growing say 10 t/ha grain produces 18 t/ha of biomass above ground and an estimated 1.8 t/ha in roots below ground. Around 46% of this biomass is carbon, and carbon makes up 27% (12/44) of carbon dioxide. A typical grain crop therefore fixes around 34 t CO_2/ha. However, this carbon is released back into the atmosphere when the grain is consumed and when its residues decompose in the soil. Unless some of this carbon is retained, for example within stable soil organic matter, there is no net reduction of atmospheric carbon dioxide. So, carbon fixation by crops is not normally considered in GHG calculations.

GHG intensity per tonne output

From a crop product perspective, what matters is the GHG intensity per tonne of grain, so the emissions per ha are divided into the grain yield. Intensities from our analysis of the Yield Enhancement Network (YEN) dataset (where sufficient information on inputs was available) are shown in Figure 1.

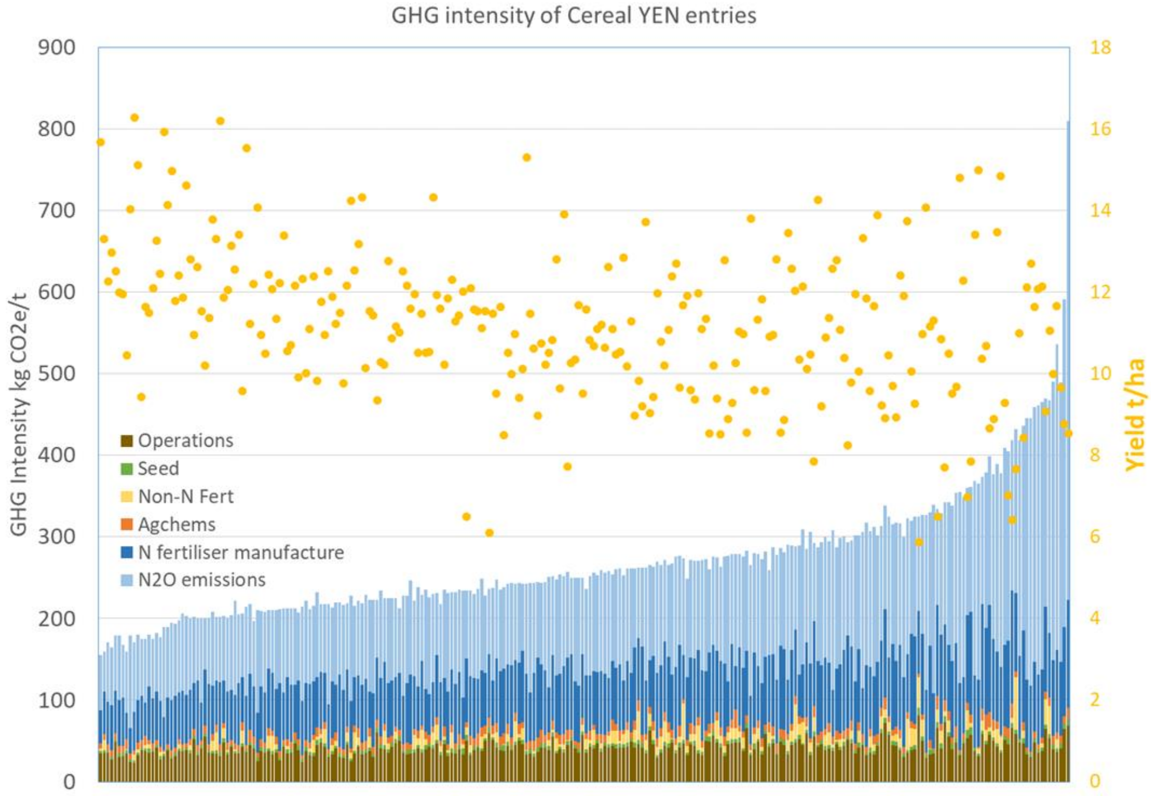

Figure 1. Estimated GHG intensities for cereal crops entered in the YEN from 2013-2019 showing all constituent parts (columns, left axis), along with yields achieved (dots, right axis).

Figure 1 clearly shows the dominance of N fertilizer and N_2O emissions on the carbon intensity of cereal grains; together these account for more than 70% of the total. There is some variation between farms in the costs from non-N fertilisers and from machinery use, mostly reflecting differences in establishment methods.

It can also be seen that the lowest GHG intensities per tonne are often achieved where the yields are high, and vice versa. However, the biggest drivers of variation in GHG intensities are the emissions from N fertilizer use and associated N_2O emissions.

The relationship between N fertilizer use, yields and GHG emissions

Let us look more closely at the relationship between N fertilizer use, yields and GHG emissions. N_2O emissions from the soil result from the nitrification of ammonium to nitrate and, in anaerobic conditions, from denitrification of nitrate or nitrite to the gases nitric oxide (NO), N_2O and di-nitrogen (N_2). From a GHG national inventory calculation perspective, all additions of N to the soil are associated with emissions of N_2O, with an IPCC (2006; 2019) aggregated default emission factor of 1% of N applied lost as N_2O. This applies not just to manufactured N fertilisers, but also to applied organic materials (e.g. livestock manures, compost, biosolids, digestate etc.) and importantly also to the incorporation of crop residues. As well as these direct N_2O emissions, indirect N_2O emissions from N that is assumed to have been leached or volatilized are also counted and included. Care is needed as the various footprinting tools use different emission factors and different approaches to calculating N_2O emissions.

ADAS led the cross-industry MINNO project from 2009 to 2015 to improve understanding of N_2O emissions from arable crops (Sylvester-Bradley et al., 2015). It found that typical emissions from ammonium nitrate (AN) fertilizer applications in the drier arable regions of the UK were substantially less than the 1% IPCC default emission factor, but it also concluded that emissions were more from wetter soils. The data from MINNO has been combined with other UK studies to revise the way that N_2O emissions from AN fertiliser are calculated in the UK National GHG Inventory. The emission factor now increases substantially with annual rainfall. This means that applying 200 kg N/ha in dry regions with 600mm annual rainfall gives N_2O emissions of 0.66 t CO2e/ha, whereas the same application in a wetter region with 1,200mm rainfall would give emissions of 1.7 t CO_2e/ha Currently in the UK GHG inventory, the N_2O emission factor from the application of urea fertilizer is not related to rainfall, so 200 kg N/ha applied as urea is calculated to give N_2O emissions of 0.7 t CO_2e/ha whatever the rainfall. Indirect N_2O emissions from urea fertiliser are, however, higher than from AN fertilizer due to the greater loss of ammonia by volatilization. The calculated N_2O emissions from crop residues (both above ground and below ground) can also be large. These are calculated using the default IPCC methodology and relate directly to the yield achieved, and amount to 0.35 t CO_2e/ha for a wheat crop yielding 10 t/ha grain. Given the high carbon:nitrogen ratio of cereal straw it is unlikely that such N_2O emissions occur immediately after incorporation, or even within a year, though this issue is being investigated in the current ResidueGas ERA-GA project (ResidueGas, 2020).. The inclusion of residues in the calculation of a crop's footprint can be problematic, as it makes the removal of straw look beneficial in the calculated GHG intensity. This is particularly an issue because the possible carbon benefits of incorporating straw into soil are not accounted for in the National GHG inventory.

Furthermore, whilst the equivalent of around 4 t/ha of carbon (~15 t CO_2e/ha) may be returned to the soil in straw, the proportion of this (if any) that would be retained in the soil in the long term is uncertain, and depends on soil conditions and cultivations. For comparison, if farming had a carbon sequestration target of 4 parts per 1000 as adopted in France (4 per 1000, 2018), then soil carbon would need to increase by around 300 kg C/ha per year, which would be equivalent to stabilising around 7% of the carbon in a crop's residues, equivalent to fixing 1.1 t CO_2e/ha.

There is a similar issue with the calculation of N_2O emissions from application of manures and other organic amendments; N_2O emissions are calculated on the total N content of the material, not the 'available N' content, and no estimate is made of the carbon that may be retained after incorporation. This means that, from a carbon accounting perspective, the use of manures and composts can make the GHG intensity of the crop look worse than if manufactured N fertiliser was used, despite the multiple benefits of organic amendments.

The importance of N fertiliser to crop GHG emissions raises questions of whether and how N rates should be adjusted to optimise crop GHG intensities. We looked at this in 2008 and have now updated the analysis in Figure 2 below using a typical N response curve for wheat and up-to-date emission factors. Figure 2 shows how, as yields increase with increased N fertiliser rates (i) embedded emissions associated with machinery, seed and other inputs reduce on a per tonne basis, and (ii) how emissions associated with N fertiliser increase. Overall, GHG intensities increase quickly with N applications, with the minimum GHG intensity achieved at only 30 kg N/ha, compared to economic optimum for yield of around 200 kg N/ha. However, this calculation ignores the consideration that any grain that is not produced here due to lower N rates and lower yields will likely have to be produced by increased production somewhere else, assuming consumer demand for grain doesn’t radically fall. Lost production here will probably be met by increasing areas of production elsewhere in the world, increasing pressure for land use change and the consequent huge carbon losses from vegetation and soil that result from the conversion of natural grassland or forest to crop land. Obviously there are large uncertainties and assumptions in trying to quantify the scale of consequential emissions from indirect land use change (ILUC), but the same ILUC argument has long been applied with the use of crops for biofuels, originally advocated by Tim Searchinger in 2008 (Searchinger et al., 2008). Here we’ve used conservative estimates to assess the ILUC consequences from changes in production caused by increasing N rates. We have shown that, at low N rates with low yields the emissions from ILUC dominate embedded emissions, and that the minimum GHG emissions are seen at N rates much closer to the economic optimum. In fact, there is little difference in overall emissions between N rates of 100 and 200 kg N/ha!

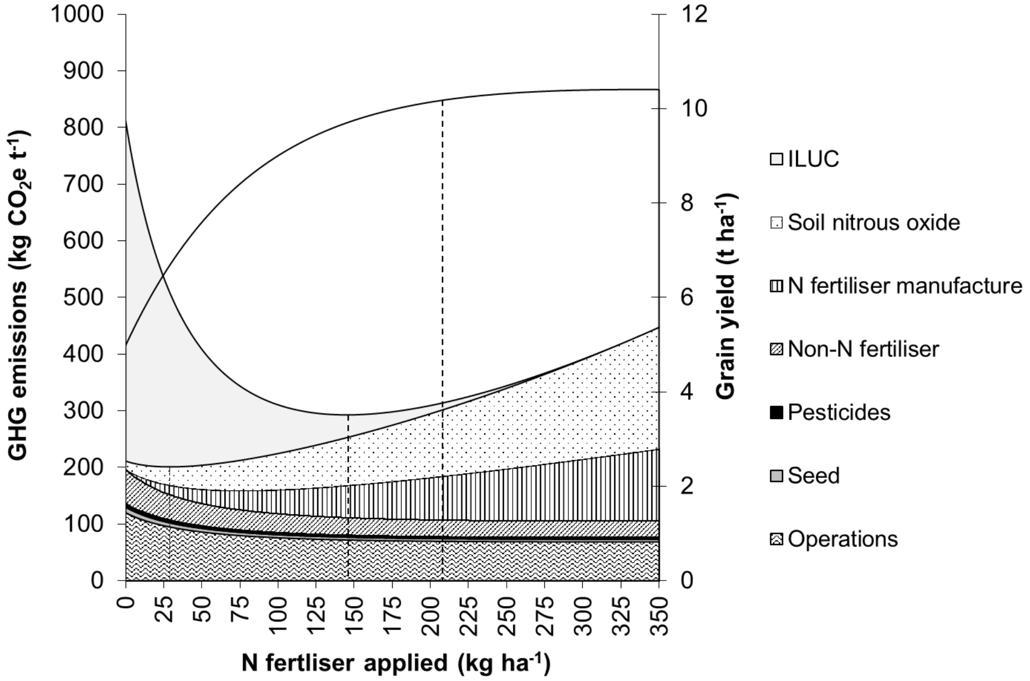

Figure 2. GHG intensity from a typical wheat crop on a per tonne grain basis showing how the constituent sources of embedded emissions change as N fertiliser rates increase and yields increase (solid line, right axis). The consequences from lost production on Indirect Land Use Change (ILUC) are also shown. Vertical dashed lines show rates that are economically optimal for yield (right), that minimise grain GHG intensity without ILUC (left) and that minimise GHG intensity including ILUC (middle).

Carbon opportunity cost

The ILUC consequences of differences in production can also be applied more broadly, with increases in yields, whatever the cause, reducing pressure on ILUC and potentially 'sparing' land that can be used to revert to natural habitats or woodland and sequester carbon. Andrew Balmford and Zoology colleagues at Cambridge University have long been arguing that the best way to protect biodiversity is to support increases in yield on productive land, sparing more marginal land (Balmford et al., 2018). In 2016, with Cambridge University, we calculated that feasible yield increases in the UK could spare enough land to reduce UK GHG emissions by up to 80% (Lamb et al., 2016).

Given the importance of ILUC, but also its uncertainties, Tim Searchinger proposed the concept of a Carbon Opportunity Cost (COC) to recognise carbon costs from lost production (i.e. carbon benefits from land sparing) (Searchinger et al., 2018). He showed that these costs are huge relative to the embedded GHG emissions from crop production; the default carbon opportunity cost for wheat grain was 1.8 t CO_2e/t, whereas our calculated embedded emissions are only around 0.4 t CO_2e/t. The implication is that producing 1 t less wheat grain in the UK will result in emissions of 1.8 t CO_2e elsewhere in the world where land is converted to meet the shortfall. This puts a high cost on the removal of arable land from production for the purposes of carbon sequestration; if the land previously produced 10 t/ha grain it would need to sequester more than 18 t CO_2e/ha/year to begin having a net benefit on global CO_2. This also suggests that there is a large under-recognised benefit from enhancing yields. Each extra tonne of grain achieved on-farm can be seen as saving 1.8 t CO_2e emissions by reducing ILUC. Many farms in the YEN consistently achieve yields >12 t/ha, where national average yields are 8 t/ha. Following Searchinger, it could be argued that these farms are having an impact of 7 t CO_2e/ha through reducing ILUC.

The YEN data show only weak relationships between inputs and yield, and little of the variation in the YEN can be explained by weather or soil type. Much more important seems to be the 'Farm Factor' where it is the attention to detail in management of the crop and soil that pays, not the amount spent on inputs (Sylvester-Bradley et al., 2019). Striving for high yield is about capturing and converting the crop's real resources of light energy and water to fix more carbon from the atmosphere. Our analysis is therefore persuading us that achieving high yields should be seen as an environmental good, rather than indicative of environmental harm.

Conclusions

Understanding, quantifying, and reducing the GHG footprint of cropping is going to become increasingly important in the coming years as the farming industry strives to reach 'Net Zero'. There will be opportunities for arable farmers to play a role in mitigating climate change through practices and technologies that reduce emissions and that lock up carbon in the soil, or by converting more marginal land from production to carbon storage. It will be crucial to this quest that the underlying GHG calculations are open and transparent, that they have consensus across the industry, and that they appropriately reflect the real global consequences of decisions made on each farm. They need to avoid the potential for 'game-playing', by reducing emissions on paper without having a real effect, and they must not disincentivise practices that are good in reality but look poor on paper. Where there is a change in quantity of production, the full consequences of that change need to be considered, including consequences on indirect land use change elsewhere in the world.

It is great that many farmers are now using the range of available carbon calculators (e.g. Cool Farm Tool, Agrecalc, Farm Carbon Calculator) to assess their GHG emissions and potential for mitigation. However, it will be important for users to understand the significance of the assumptions made by each calculator so they can achieve the comparisons that they want.

Having led the use of benchmarking in the YEN to understand yield determination on farms, ADAS now can see the potential power of utilising the same approach to address the opportunity to reach Net-Zero. We are really pleased to have created YEN-Zero in summer 2021 to bring together a community of interested farmers, advisors, industry, researchers and policy makers, to develop shared understanding, to share ideas and data, to enable comparisons and benchmarking, to derive insights and to form hypotheses that can be tested on-farm.

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