A roadmap to reducing greenhouse gas emissions from the Scottish potato crop.

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[1] Scottishpotatoes.org is a partnership between SRUC and JHI

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Summary

Data from an analysis of potato growers who have submitted a carbon footprint in the Agrecalc system showed the carbon footprint associated with growing potatoes. This demonstrated that the carbon footprint associated with the growing of potatoes is determined predominantly by (a) use of nitrogen fertilisers which contribute both through the indirect energy requirements of production and the nitrous oxides associated with their use (b) the requirement for diesel powered vehicles to cultivate and harvest the crop and (c) the requirement for electrical energy to store the crop.

The yield of crops is a key determinant of the carbon footprint, expressed as carbon emissions per tonne produced. High yielding crops have lower footprints per tonne produced than low yielding crops.

Considerable variation was present between growers producing for different sectors and within each sector. Thus, some growers appear to be highly efficient with significantly smaller footprints than others. This provides, for most growing operations, a clear opportunity to improve.

A roadmap which focuses on the three areas identified above combined with yield improvements can deliver significant improvements to the carbon footprint of potatoes. By bringing together targets for reductions in Nitrogen use, reductions in diesel use and improved store efficiency, a clear route towards reducing the carbon footprint by over 30% has been identified. This roadmap assumes that growers can become more efficient and produce more tonnes while utilising fewer resources. Some growers in the dataset were demonstrating that they are already significantly more efficient than others.

The roadmap looks only at the actions that can be taken by potato growers within the year of production. Further improvements to the emissions from potato growing can be expected when changes to the land management and sequestration from other sources is considered within the rural environment.

After implementation of the roadmap, further developments and innovation will be necessary to continue the journey towards net zero. A number of areas are identified which have the capability of impacting on the sustainability of potato production in the future.

Introduction

The Scottish Government has committed to reaching net zero emissions by 2045. Agriculture represented a significant proportion (16%) of Scotland's emissions in 2018[2].

The Scottish Government's Climate Change Plan update requires the equivalent of a 31% reduction in agricultural emissions by 2032 from 2018 levels[3]. Between 1990-2019 Scottish agriculture's emissions decreased by only 13%.

Potatoes are an important part of the arable landscape of Scotland, employing over 2000 people and delivering £250 million to the economy[4]. Scottish seed potatoes have a worldwide reputation for quality, supplying 77% of the seed for a £928 million GB potato industry and exports worth £55 million. Potatoes provide a healthy source of fat free, low sugar, low salt source of fibre rich in potassium, and vitamins B_6 and C. The crop represents a significant part of Scotland's cultural heritage. It is thus imperative that the potato sector look to reducing its contribution to the overall emissions targets.

In August 2022 a workshop "Delivering net zero potatoes to consumers" comprising members of SEFARI institutes; SRUC and JHI along with representatives of SAOS and SASA was convened by Scottishpotatoes.org a partnership of SRUC and JHI. This specialist group reached a number of provisional conclusions surrounding the route the potato sector needs to take to bring it onto pathway towards net zero. In essence, a significant reduction in emissions by 2032 (around 30%) is achievable based on current knowledge base. However, the sector is not considered on track to achieve this. Particular concerns were raised over inconsistent messaging and the implementation of practices understood by specialists but poorly executed in practice. It was agreed that a whole supply chain approach was necessary to ensure maximum carbon reductions are delivered. Engagement with supply chain actors indicates that the issue is high on their agenda, but that understanding of the impact of different strategies is poorly understood and sometimes contradictory.

A holistic approach is required to ensure maximum short and medium term carbon reductions are delivered with a clear evidence based roadmap applicable to all stakeholders. This special advisory group would seek to engage with the supply chain to produce a roadmap of activities applicable to all subsectors within Scottish potato production.

Aims and objectives

1. To engage with specialist scientists at SEFARI institutes to bring together an evidence based document which details actions that can currently be undertaken by potato supply chains to reduce GHG emissions.

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[2] Barnes et al (2023) Reducing emissions from agriculture – the role of new farm technologies.
A report for Agricultural Policy Division. February 2023. Supporting documents - Reducing emissions from agriculture – the role of new farm technologies - gov.scot (www.gov.scot)

[3] Securing a green recovery on a path to net zero: climate change plan 2018–2032 - updatehttps://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

[4] PCN Working Group Final Report | Potato Cyst Nematode Hub (pcnhub.ac.uk)

2. To engage with stakeholders to develop a practical, economically viable and agreed two part roadmap for supply chains to follow in order to reduce GHG emissions from their potato production activities. Part one will outline actions that can be taken immediately to reduce emissions. Part two will look at the science needed to continue the journey towards zero.
3. Dissemination and uptake of the roadmaps by industry and policyholders.

Scope

Potatoes are but one piece of a complex rural economy and interactions between the different parts of this system impact on the carbon footprint of the potato crop. The objective of this work is to identify those actions that can be taken by potato supply chains to reduce carbon emissions, while understanding that other sections of the rural economy impact on the carbon footprint of the crop within this landscape.

Potatoes are frequently grown on land rented on an annual basis. This approach ensures that rotations are both sustainable and viable while allowing economies of scale from larger producers. However, the rotational management of the land lies with the landowner rather than the potato producer. Wider management of the land base, impacting on the overall carbon footprint of the rural sector lies with the landowner. This study limits itself to the actions that can be taken by growers in the production of the potato crop itself.

Engagement Activity

The development of the roadmap and the evidence supporting it was discussed at stakeholder meetings on 2nd August and 6th September and 2023. Representatives of IPM Potatoes, Agrico UK, GB Potatoes, Albert Bartletts, Morrisons growers and retail, Seed Potato Organisation, McCain and KP snacks were present at these meetings and the discussion and feedback has been incorporated into the report.

Analysis of Agrecalc data

Agrecalc (https://www.agrecalc.com/) is a farm carbon calculator developed by SRUC and used widely in the agricultural sector.

The calculator uses equations published by the Intergovernmental Panel on Climate Change and the UK Government to estimate greenhouse gas emissions from all major on-farm and upstream sources. Agrecalc is based on the life cycle assessment (LCA) framework for evaluating the environmental impacts of products and processes. The model calculates all greenhouse gas emissions related to agricultural production, up to the point when final products leave the farm gate. Outputs include estimates of all major greenhouse gas emissions (CO_2, CH_4, and N_2O) from the farm and its products.

Anonymised data from Scottish potato producers, divided into four categories (Early production, Maincrop processing, Maincrop ware and Seed) was downloaded and analysed for the purposes of this report.

The data consisted of information from 221 Scottish based businesses growing potatoes. The data was provided during June 2023 and relates to the most recent annual return from each business, this would be either the 2022 or 2021 growing season depending upon the reporting timescale of different businesses.

During the analysis a number of datasets were removed as they were deemed unreliable or unrepresentative of standard practice. This included business with no apparent diesel use allocated to potato production, yields of less than 20 t/ha, and outliers with very high nitrogen use. This resulted in a total dataset of 211 businesses (12 Early, 13 Maincrop processing, 121 Maincrop ware and 65 seed production).

The carbon footprint for the potato crop, excluding figures for sequestration, has been presented in the Appendix as the carbon footprint per hectare grown and per tonne produced. Sequestration figures have been excluded as these are derived from whole farm figures allocated across different enterprises. Although sequestration has an important part to play in the carbon footprint of agricultural businesses, this report aims to focus on the emissions caused by potato growing alone as described on page 6 (Scope).

Throughout this report figures for carbon footprint are presented throughout as Kg CO_2 equivalents per tonne produced or per hectare grown. Data is generally presented as an Average, Standard deviation, Count (n), 90th Percentile and 10th Percentile.

Farm data

The average farm size in the Agrecalc data set is 62.7ha (Table Appendix A4). There is a considerable range in potato crop area reported through Agrecalc. Recent data on production is limited since AHDB Potatoes ceased to function. However, in 2018 the majority of GB growers were growing between 10-29 ha and 30-99ha (Figure 1).

Similarly, the average yield, across all sectors, is 45.4 t/ha. As would be expected, the average yield of early (33.0 t/ha) and seed (37.3 t/ha) crops is less than the overall average, while processing (48.7 t/h) and ware (50.6 t/ha) is above the average. These figures also correspond closely to those produced by AHDB for GB growers as a whole (Figure 2).

The available dataset therefore does provide a reasonable reflection of the potato sector in Scotland.

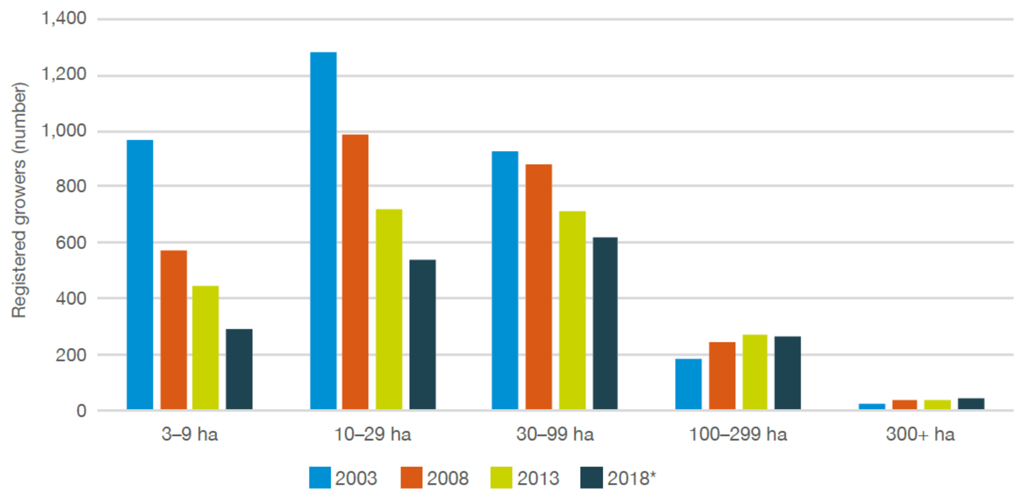


Figure 4. Number of potato growers by size band in hectares

Notes: 2018*, provisional data as at November 2018

Figure 1: Number of potato growers by size band in 2003, 2008, 2013 and 2018[5]

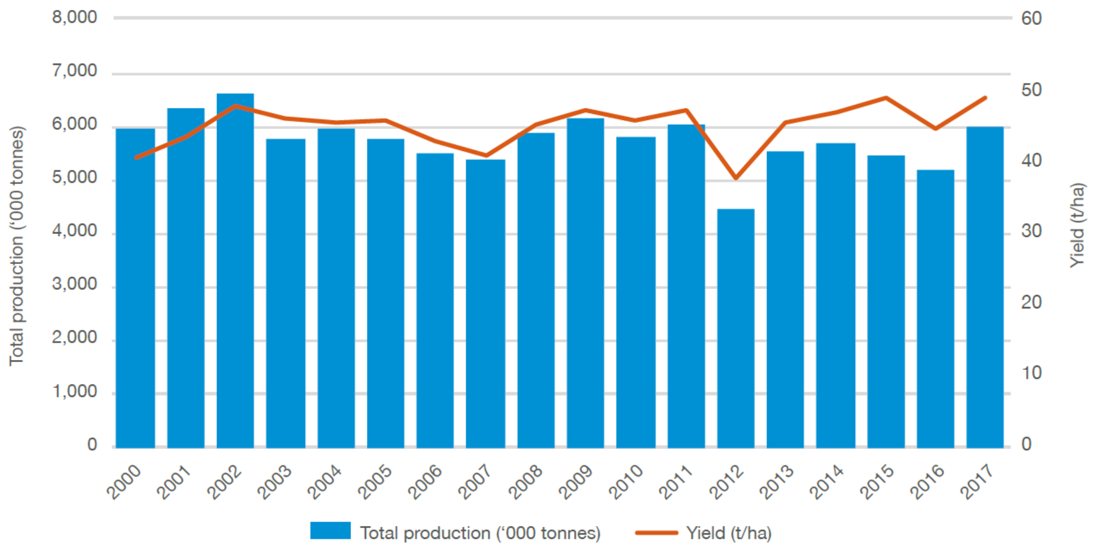


Figure 1. Yield per hectare and total production

Figure 2: Total production and yield per hectare for GB (years 2000-2017)[6]*. From "GB Potatoes: Market intelligence 2018-2019.*

[5] Reproduced directly from "GB Potatoes: Market intelligence 2018-2019. AHDB Potatoes 2019.

[6] Reproduced directly from "GB Potatoes: Market intelligence 2018-2019. AHDB Potatoes 2019.

Direct Carbon emissions (Diesel Fuel)

Agrecalc evidence

Table 1 provides a summary of the total direct energy use for different potato business types. Across all grower types an average of 34 Kg CO_2 were emitted due to fuel use per tonne. The range between growers (10th to 90th percentile) was 15.5 to 56.0 Kg CO_2/t (or 701 to 2349 per ha). This shows a range in energy in excess of a factor of 3.

Table 1: Carbon emissions from direct use of fuel.

	Total emissions (Kg CO_2/tonne) produced	Range (10th to 90th percentile)	Total emissions (Kg CO_2/ha) grown	Range (10th to 90th percentile)
Early	40.5	25.2-67.3	1246	744-2052
Processing	34.9	9.9-47.9	1665	547-2174
Ware	31.8	16.5-50.6	1563	772-2484
Seed	37.1	13.8-59.8	1325	474-2000
All crops	34.1	15.5-56.0	1477	701-2349

Use of diesel

Diesel represented 69% of direct emissions from fuel across all growers. Seed and early production used less diesel on average (995 kg/ha, 971 kg/ha respectively) than maincrop ware or processing (1031 kg/ha, 1115 kg/ha) per ha (Appendix Table A1). However, in terms of each tonne of potatoes produced the situation was reversed. Seed and early production produced 28.0 kg CO_2 per tonne, 32.0 kg/t, respectively, higher than the average for maincrop ware and processing (20.8 kg/t and 20.8 kg/t (Appendix Table A1).

There is a considerable range in the amount of CO_2 released from diesel used per hectare, with an average of 1022 and upper and lower percentile of 1534 and 469. However, there appears to be no relationship between the amount of diesel used and the yield (tonnes/ha) (Figure 3).

This would appear to indicate that reductions in diesel use could be made by some businesses without compromising yield.

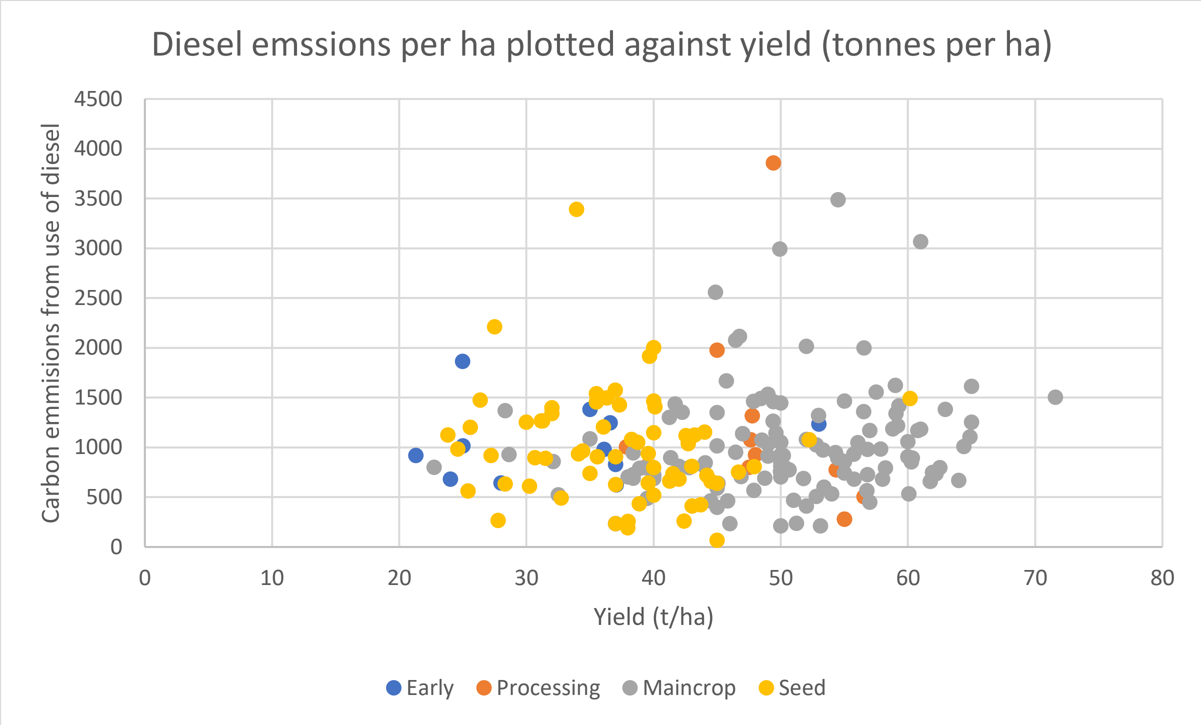


Figure 3: Yield per ha plotted against the CO_2 emissions from diesel use.

Current situation

Diesel use in individual potato businesses will depend upon many factors. These include the power and size of machine being used, depth of operation, correct calibration, appropriate maintenance, speed and care of operation, as well as individual field factors such as soil type and stone content, yield and frequency of spray applications. The estimated average fuel consumption for different activities is presented below (Table 2).

Table 2 Estimated fuel use in different field operations (Farm Management Handbook, 2022/2023[7])

Operation	Diesel use (l/ha)
Ploughing	29.75
Heavy cultivation	19.13
Light cultivation	4.02
Power harrow	26.78
Fertiliser spreading	1.57
Potato planting	14.40
Spraying	1.96
Towing (trailer)	6.48
Potato harvesting	49.37

Intensive diesel use occurs at both ends of the potato season (soil cultivation, harvesting). The majority of businesses do not monitor fuel use of different machines or operations. Most will require more information to ensure that savings can both be made and recorded.

[7] Beattie (editor) 2023. Farm Management Handbook 2022/23. Farm Management Handbook 2022/23 | Information helping farmers in Scotland | Farm Advisory Service (fas.scot)

During planting operations there is considerable scope for alterations to cultivation before and during potato planting operations. Growers have an opportunity of reducing their use of inversion tillage (ploughing) in favour of less fuel intensive cultivations. Depending upon soil type and the individual field situation, bed tilling can be reduced. However, destoning, an energy intensive operation is generally considered an essential operation for Scottish soils.

The amount of diesel used each season will depend to some extent on the soil conditions present at the time. However, experience shows that delaying planting until soil conditions are suitable will result in better crop performance and require less energy. Thus, seasonal variation in the use of diesel for planting, per ha, should be relatively small irrespective of the season. In a late season where total yield has been compromised by late planting the fuel use per tonne produced could be increased.

Evidence from AHDB SPot Scotland demonstration trials (unpublished) indicated potential savings of diesel use during planting of 54% (comparing minimum to maximum fuel use regimes). Reductions in the intensity and depth of cultivation did not affect yield or quality.

In other work investigating destoning depths on potato yield and production, Stalham and Alison 2015[8] found that shallower destoning with reductions in energy use tended to result in slightly improved yields (Figure 4).

Figure 53. Effect of destoning depth on yield (difference between actual and standard) in all destoning depth experiments conducted in 2011-2014. SCI-C experiments, ■ and solid line (y = -0.25x - 0.36, R^2 = 0.33); SL experiments, □ and dashed line (y = -0.176x-0.34, R^2 =0.45).

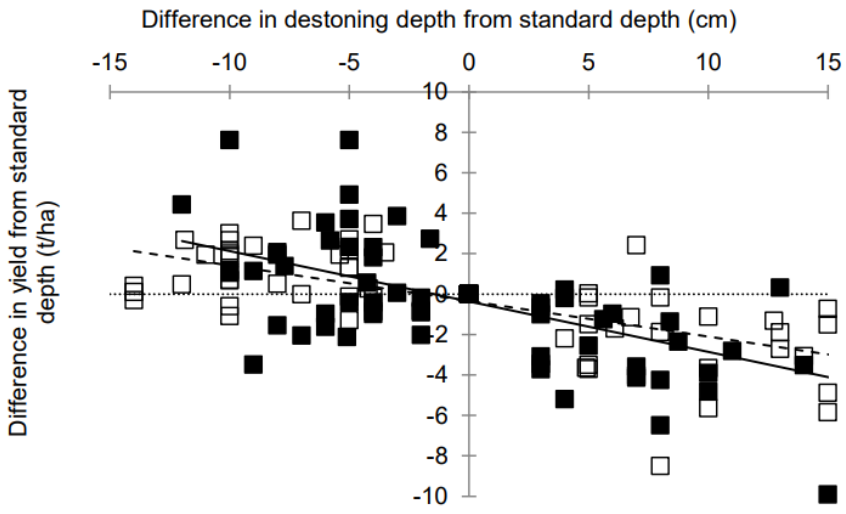


Figure 4: Graph showing the effect of reduced and increased depth of destoning operations in a range of potato crops[9].

[8] Stalham and Alison (2015). Improving cultivation practices in potatoes to increase window of workability and soil structural stability. AHDB Potatoes report. R459 Cultivations FINAL.pdf (windows.net).

[9] Reproduced directly from Stalham and Alison (2015). Improving cultivation practices in potatoes to increase window of workability and soil structural stability. AHDB Potatoes report. R459 Cultivations FINAL.pdf (windows.net)

During the growing season the potential for diesel use reduction is less. The main use will be related to spraying operations. Such use could be reduced by larger machinery (wider boom width) or a reduction in the number of passes (fewer spray applications). Such reductions may be achieved through the use of more resistant varieties or more effective chemical regimes (e.g., using a single pass for herbicide application or longer intervals between blight fungicide applications). Organic methods of weed control (mechanical cultivation) and haulm destruction (e.g., gas burning) will increase the amount of diesel required.

Irrigation of crops and the pumping of water also requires energy. Use will be dependent upon equipment, distance and water availability. Varieties which can be grown without, or with less, irrigation can be considered to reduce this requirement for energy.

Pulverisation of crops to destroy haulm has been standard practice since the withdrawal of firstly sulphuric acid and later diquat as means of haulm destruction. New developments such as haulm pulling, or electrocution should be evaluated for effectiveness in the field and as a means of reducing energy use. However, the carbon footprint implications of these new techniques needs to be considered carefully.

Harvest is also an energy intensive operation involving considerable soil movement, alongside use of trailers and transport. Soil conditions at this time will result in large variation in the amount of fuel used from one season to the next. Climate change and the advent of more variable weather can in some instances result in difficult harvest conditions with wet and heavy soils from which separation of the crop becomes an energy intensive operation. Soil management practices will have an impact on this situation, but extreme weather events will overwhelm any improvements in soil structure achieved by rotational management of improved cultivation at planting. Efficiency of operations, i.e., management of trailers, logistics and store loading, will also have an impact on energy use.

Reducing diesel use

Given the large variation in diesel use across different businesses and the lack of an apparent relationship to yield there is a considerable opportunity for some businesses to reduce diesel use through a range of mitigations. High fuel using businesses should be targeted for the greatest reductions in diesel use. However, even more efficient businesses will always be able to identify savings.

Targets

	Timescale	Target reduction	Actions
Stage 1	1-3 years	10%	High users will be able to make simple efficiencies
Stage 2	4-6 years	20%	Improvements in efficiencies combined with improvements in cultivation practices
Stage 3	7-10 years	30%	Achieved through improved practices and changes to land management and choice.

Evidence required and barriers to uptake

- Accurate fuel use figures from individual businesses for each operation.
- Greater knowledge of how to reduce energy use in the field.

- Confidence from growers to make operational changes to growing systems.
- Matching water use efficient varieties to the market requirements for variety end use.
- Soil management requires a rotational approach and much potato land is rented on an annual basis.

Direct Carbon emissions (Electricity)

Agrecalc evidence

Electricity use is responsible for an average of 25% of the emissions related to fuel use (per ha). Together with diesel, this represents 94% of the total emissions related to energy. (Appendix Table 1A). Electrical energy is used primarily in the storage of potatoes for ventilation and refrigeration. Crops initially must be dried (or cured) before being brought down to holding temperature. Stores can be either 'ambient' or ''refrigerated'. In ambient systems outside air is used as and when available to ventilate and cool the crop. As climate change results in warmer temperatures the opportunities for ambient control have reduced. The change from ambient cooling has also been accelerated by higher quality targets for all markets. Refrigerated systems use mechanical means to cool air and control the temperature of the crop and a large majority of stores are now refrigerated. Electrical energy will be used for grading operations, water pumping (if not using diesel) and a proportion of general farm use.

As would be expected, early potatoes which are usually stored for short periods have the lowest average electricity use (average 165 Kg CO_2/ha). The highest use was for maincrop ware potatoes (average 449 Kg CO_2/ha); most of these crops will be stored for between a few weeks and 9 months to ensure continuity of supply to retailers. Seed and processing crops recorded an average of 258 and 310 Kg CO_2/ha respectively.

Ware and seed crops will generally be stored in refrigerated systems at temperatures of between 2.5 and 4°C. Processing crops will be stored at warmer (7 to 10°C) temperatures to ensure processing quality is maintained. Higher storage temperatures are less energy intensive and more often reliant upon ambient air.

Renewable energy sources can be used to supply a proportion of the energy required for storage, although this was not taken into account in the present analysis. Irrespective of the source of energy it is necessary to use it efficiently and reduce costs. This enables excess self-generated renewable energy to be used to offset emissions from other parts of the production system.

Electricity prices have increased considerably over the past year. Growers who use large amounts of electricity have focused more recent attention on reducing electricity use.

Current situation

A considerable amount of evidence was produced by Sutton Bridge Crop Storage Research (SBCSR) on energy use and carbon footprints of storage facilities[10]. These documents and others show the

[10] Swain et al (2013). R439 Reducing the Energy Use and Carbon Footprint of GB Potato Storage. Reduced energy storage - to minimise the carbon footprint associated with storage of GB potato crops | AHDB and

considerable variation in energy efficiency across different stores and provide guidance on improvements in energy efficiency.

The amount of energy which can be saved is highly dependent upon the age and current efficiency of the store, with modern well maintained stores proving more efficient than older stores. An audit of current efficiency is always recommended as a first step towards improving energy efficiency. In a great many cases the current energy use of potato stores is poorly understood, and greater use of energy monitoring is required to provide benchmark data for energy efficiency programs.

Reducing carbon footprint

In all situations efficiencies can be made in the use of electricity in the storage of potatoes. The following is a summary of the actions that can be taken. Further information is available at www.horticulture.ahdb.org.uk/potatoes and in particular in the Potato store managers guide[11] and the Potato seed storage guide[12]

- Target all interventions. Drying crop at harvest must be prioritised.
- Control temperature and consider small increases in target temperature.
- Consider use of sprout suppressants to allow more flexibility with temperatures.
- Record and monitor energy use in stores
- Reduce air leakage, especially relevant on older stores.
- Improve insulation.
- Ensure efficient use and movement of air in the store. Modifications (e.g., air curtains) can improve air movement and storage efficiency.
- Optimise refrigeration performance.
- Improve store control with automated systems.
- Train store management staff to focus on energy efficiency.
- Maximise renewable energy options. Ensure generation of renewable energy is twinned with control systems that maximise its use when available.

Targets

	Timescale	Target reduction	Actions
Stage 1	1-3 years	10%	Audit of store management and energy requirements. High users will be able to make simple efficiencies to store leakage and management.
Stage 2	4-6 years	20%	Investment in store modification to improve airflow and store management. Improved insulation and other moderate investments.
Stage 3	7-10 years	30%	Improve storage efficiency though new storage estate.

Swain (2010). R401 Reducing the Energy Cost of Potato Storage. Reduced energy storage - to minimise the carbon footprint associated with storage of GB potato crops | AHDB

[11] Cunnington *et al* (2019). Potato Store Managers guide. https://horticulture.ahdb.org.uk/knowledge-library/potato-store-managers-guide.

[12] Cunnington and Phillips (2019). Seed storage guide. https://horticulture.ahdb.org.uk/knowledge-library/potato-seed-storage-guide

Evidence required and barriers to uptake

- Individual store energy use records required to benchmark and to inform change.
- Training of store managers in efficient practices.
- Investment in improved or new storage facilities.
- Independent information on storage efficiency.
- Improved and updated 'user friendly' store control systems.
- Requirement for significant investment to replace existing dated infrastructure.

Indirect Carbon emissions

Indirect carbon emissions include those allocated to fertiliser use, lime application, pesticides, waste and transport. Almost all (94.5%) of indirect emissions are due to application of fertilisers (Figure 5). Early and seed crops generally have a lower fertiliser requirement than maincrops (processing or ware) and this is reflected in the data as a key driver of total energy use in potato production (combined direct and indirect energy use).

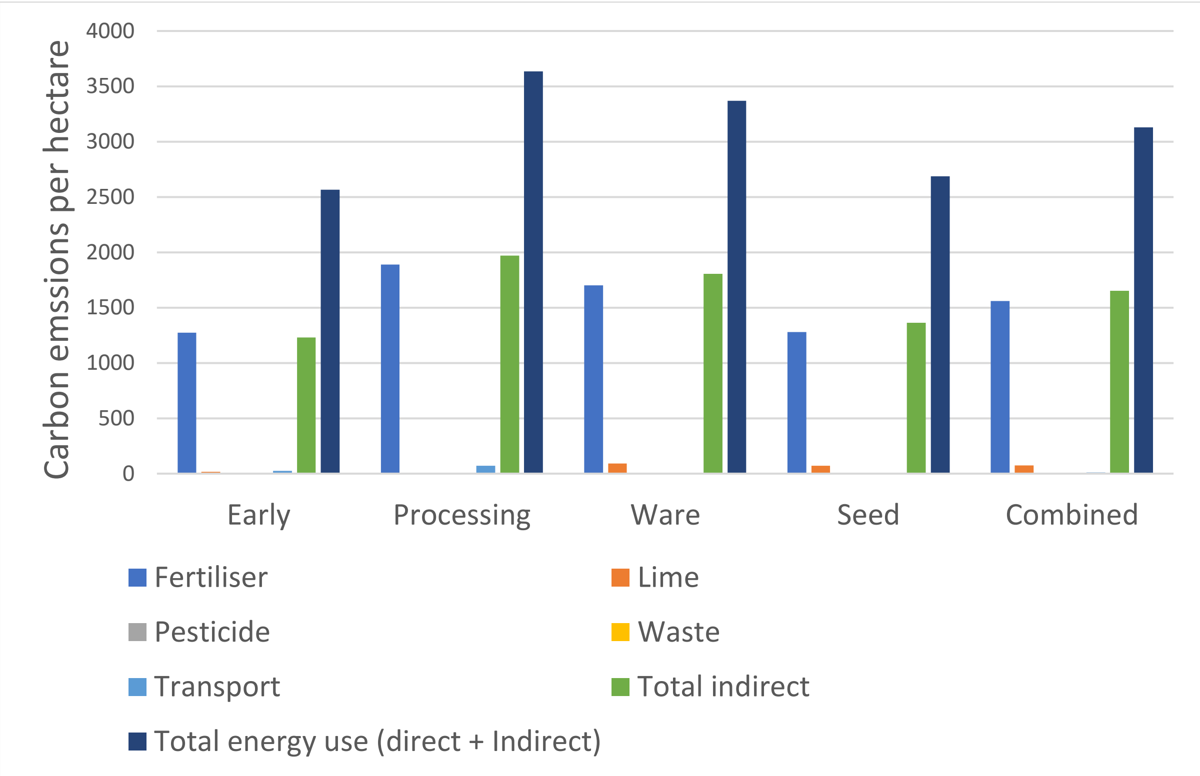


Figure 5: Indirect fuel carbon emissions (equivalent) fertiliser, Lime, pesticides, waste and Transport emissions.

Lime use accounts for the majority of the remainder (4.0%), although it is not used for potato production directly. However, application is made within the rotation and is important for the productivity of other crops in the rotation. Agrecalc generally allocates lime application equally across all arable enterprises on the farm.

The remaining sources of carbon emissions due to indirect fuel use are negligible in terms of the overall carbon footprint (Appendix Figure A3). Pesticide use is likely to contribute to a reduction in carbon footprint as applications are made to maintain or improve yield, improve product quality and reduce waste. However, additional carbon output will be required to apply pesticides[13].

Nitrous oxide emissions

Nitrous oxide (N_2O) contributes to climate change due to its positive radiative forcing effect, and the gas has a relatively high impact, with a global warming potential (GWP) of 298 compared with a figure of 1 for CO_2. Therefore, the emissions of N_2O associated both with nitrogen fertiliser use and that associated with crop residues degradation have a significant impact on the carbon (equivalent) footprint of the potato crop.

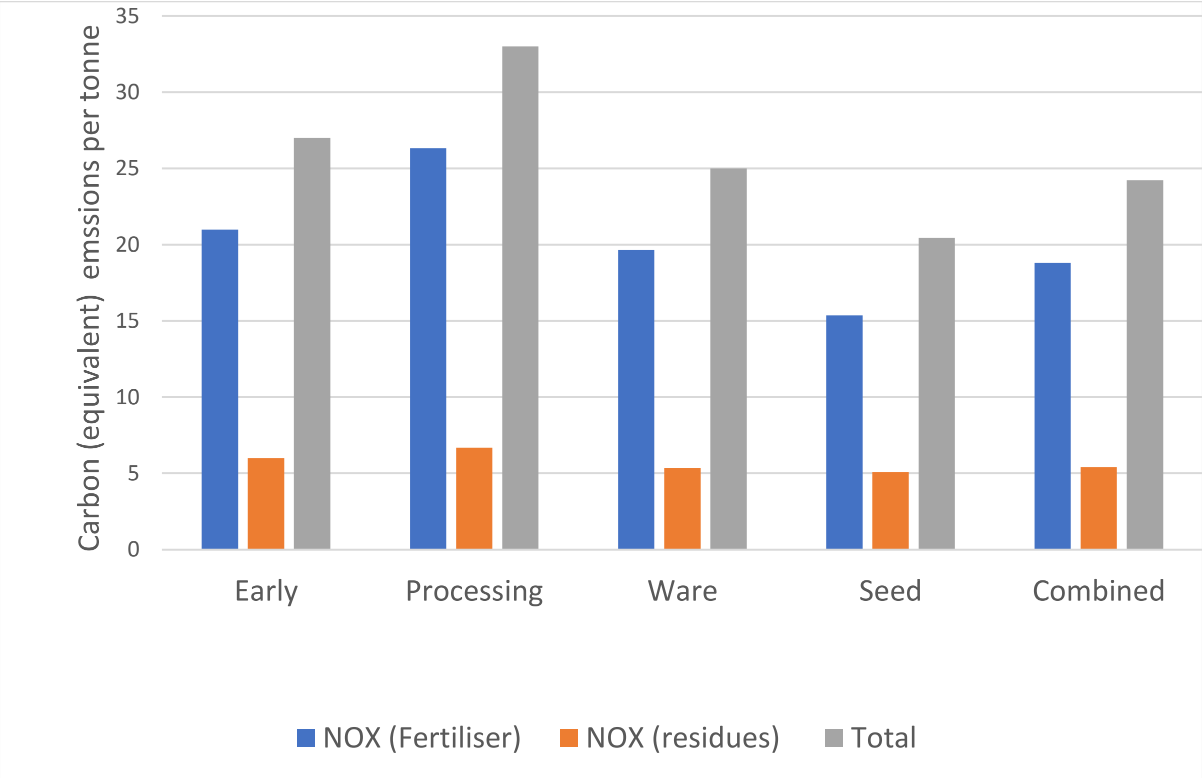


Figure 6 Carbon emissions (equivalent) related to Nitrous oxide emissions for different potato crops from fertiliser use and the effect of crop residues.

On average, N_2O emissions associated with fertiliser use and crop residues account for 77% and 23% of the total respectively.

[13] Note the figure does not include the diesel energy required to apply pesticides which is captured under direct fuel emissions.

The emissions from residues are from both above and below ground plant parts left in the field after harvest. Mitigation of this source is difficult to determine as residues are a result of crop growth and there is currently no economic use for potato haulm. Removal of residues is not practical and the benefits to soil structure and future soil productivity of returning residues is an important consideration.

R Sylvester-Bradley et al (2015) concluded that the scope for farmers to reduce NO_2emissions on arable crops was limited[14]. The impact of residues on carbon footprints can only be reduced marginally and this will be associated primarily with reductions in overall nitrogen use and improved canopy management.

Production on lighter soils with lower water use (rainfall or irrigation) will reduce the N_2O emissions from fertiliser use. Smaller canopies due to varietal differences or reduced fertiliser use would also reduce this source. However, reductions that reduce the yield potential of crops would not be considered sustainable.

Nitrogen use

The carbon emissions due to the use of fertiliser and associated N_2O emissions is considerable and combined account for an average of 57% percent of the total emissions (both on a per ha and per tonne basis) (Table 3). This proportion is generally similar across all crop types. In the case of seed, a lower rate of nitrogen use results in a small reduction in the proportion of emissions related to fertiliser use.

Table 3: Emissions from different crop types related to the use of fertiliser as indirect fuel use and Nitrous oxide emissions.

Crop type	Fertiliser indirect emissions		Nitrous oxide (C equ) emissions from fertiliser		Total emissions related to fertiliser use		Total emission from potato production		Percentage of total emissions	
	Per ha	Per tonne	Per ha	Per tonne	Per ha	Per tonne	Per ha	Per tonne	Per ha	Per tonne
Early	1273	41	668	21	1940	62	3429	110	57%	56%
Processing	1889	39	1214	26	3103	66	5178	109	60%	60%
Maincrop	1702	34	972	20	2675	54	4611	93	58%	58%
Seed	1281	35	549	15	1829	50	3423	95	53%	53%
All crops	**1559**	**35.1**	**839**	**18.8**	**2398**	**54.0**	**4211**	**95.4**	**57%**	**57%**

There is considerable variation in the Agrecalc data demonstrating a range of different approaches to fertiliser application to potato crops. However, Figure 7 Shows an apparent relationship between the indirect CO_2 emissions per ha due to fertiliser application and the total emissions produced per tonne of output. The amount of fertiliser is thus a significant driver in the carbon footprint. The small number of processing crops in this sample would appear not to follow the same trend.

[14] Minimising nitrous oxide intensities of arable crop products (MIN-NO) | AHDB

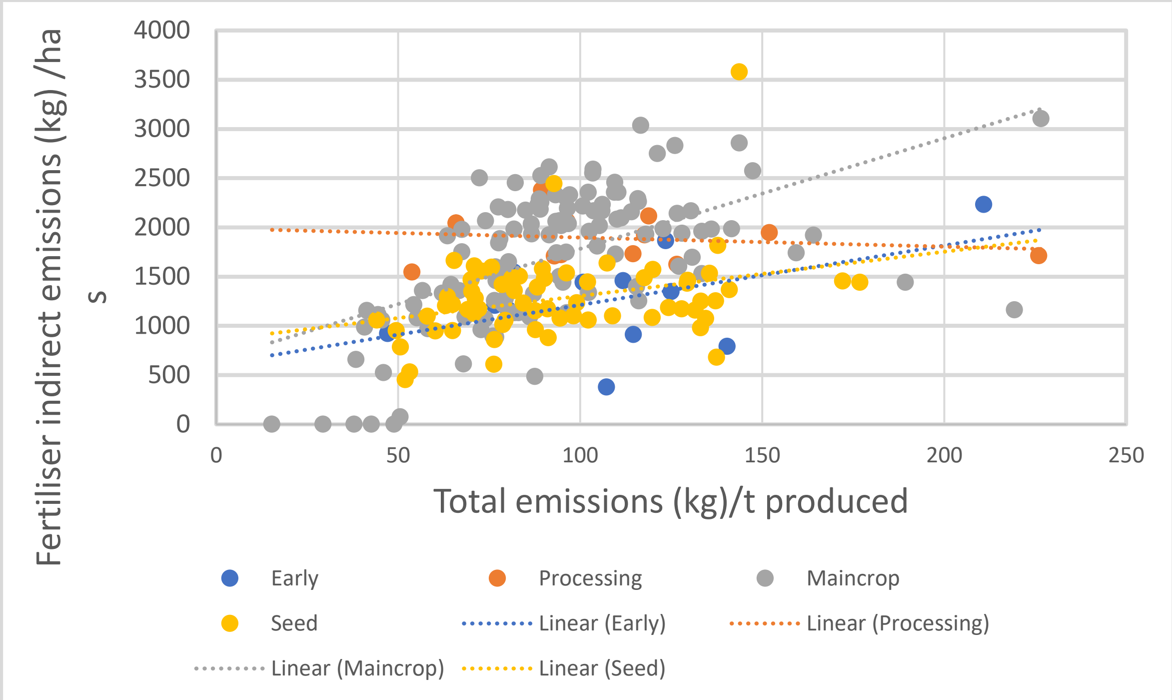


Figure 7: Scatter chart of indirect Carbon (equivalent) emissions from fertiliser use per hectare related to the total emissions per tonne produced.

However, there is also an apparent relationship between the indirect emissions from fertiliser application and the yield produced (Figure 8). As might be expected, increased fertiliser application appears to result in higher yields. The considerable variation around this trendline indicates that there are many producers producing high yields with lower fertiliser use and its associated emissions than others.

Reduction in nitrogen application is therefore a key step in the reduction of carbon emissions from growing the potato crop.

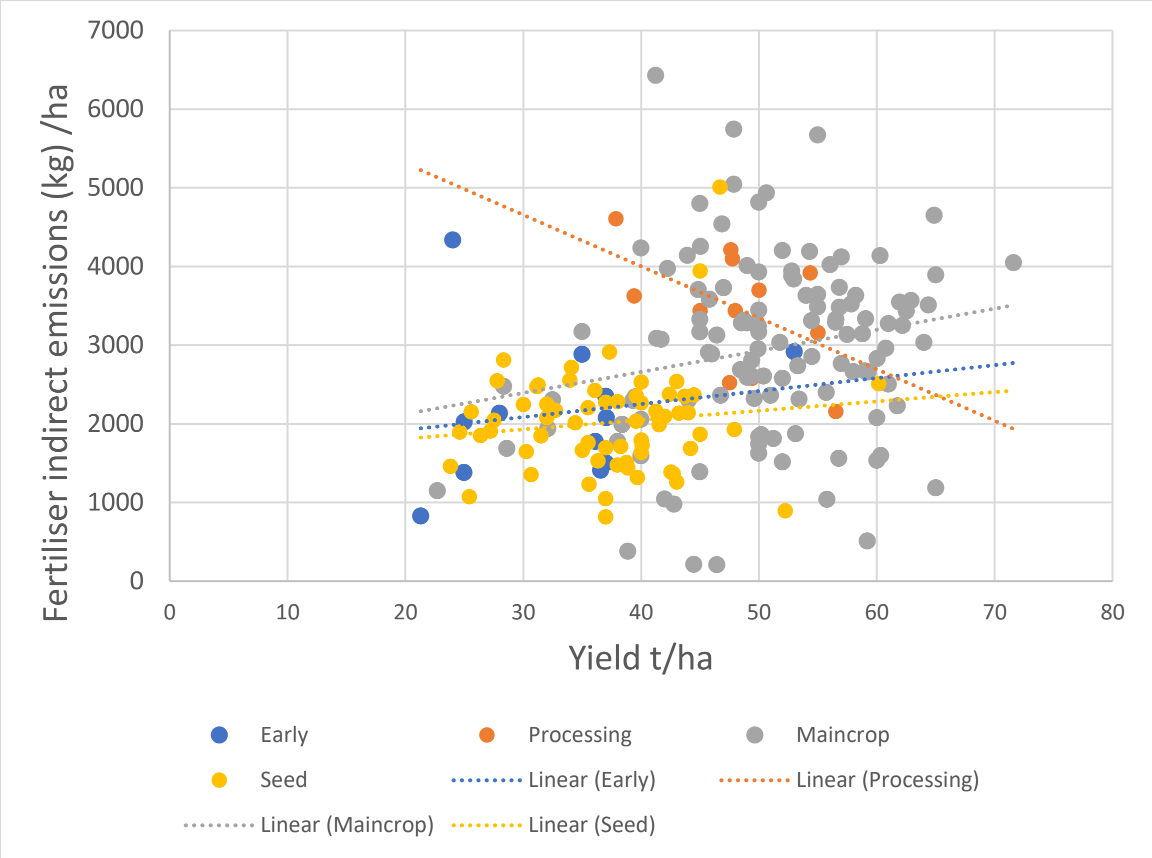


Figure 8: Scatter chart of indirect Carbon emissions from fertiliser use per hectare related to the yield (tonnes per ha).

Reducing fertiliser use in potato production

Summary of current situation.

Recommended rates of nitrogen are published for the UK and Scotland[15] and the recommended application rate varies according to the previous crop, the variety group (nitrogen determinacy) and the crop duration. This results in recommendations for applications which can range from 0 to 240 kg N per ha (SRUC recommendations). A majority of potato crops in Scotland are grown within an arable rotation providing a soil nitrogen residue class of 1 with recommendations ranging from 40kg/ha to 240 kg/ha (Table 4).

Table 4: Recommended Nitrogen application rates (kg/ha) for different varieties and crop type

Variety nitrogen determinacy group	Early potato production (< 60 days crop duration)	Seed crop (60-90 days)	Ware / processing crop (90-120 days)
1	80	100	240
2	60	80	200
3	40	60	160
4	-	50	120

[15] tn651.pdf (sruc.ac.uk) and RB209 2021 Section 5 Potatoes | AHDB.

Reducing the carbon footprint

Allison and Firman (2015)[16] between 2007 and 2014 (Table 5) studied a range of crops and compared the grower specified nitrogen 'commercial' rate with a rate determined on the basis of the current recommendations. This resulted in comparison crops receiving 28 kg/ha less nitrogen on average (a 14% reduction) than used in the commercial crop. In these trials, yield was on average increased from 56.4 t/ha to 61.0 t/ha when nitrogen application was reduced. Carbon footprint analysis was not produced from this dataset. However, the combined reduction in nitrogen application and yield improvement will have combined to ensure a significant impact.

Table 5. Extract from Alison and Firman 2015.

Table 11. **Summary showing average effects of (*a*) reduced nitrogen application rates and (*b*) reduced seed rates on total tuber population and yield and margin over seed and nitrogen cost. Data from Grower Collaboration project 2007-2014. Seed has been valued at £300/t and N at £0.90/kg. For further details see text**

(*a*)	Nitrogen application rate (kg N/ha)	Tuber population > 10 mm at final sampling (000/ha)	Tuber yield > 10 mm at final sampling (t/ha)	Margin over seed and nitrogen costs (£/ha)
Mean of standard crops (n=22)	196 ± 5.3	500 ± 23.8	56.4 ± 2.09	5054 ± 334
Mean of improved crops (n=22)	168 ± 4.9	527 ± 23.8	61.0 ± 2.54	5668 ± 391
Mean difference	-28 ± 2.5	27 ± 11.9	4.6 ± 1.52	614 ± 199
Probability difference is significant	<0.001	0.033	0.007	0.006

(*b*)	Seed rate (t/ha)	Tuber population > 10 mm at final sampling (000/ha)	Tuber yield > 10 mm at final sampling (t/ha)	Margin over seed and nitrogen costs (£/ha)
Mean of standard crops (n=41)	2.34 ± 0.132	549 ± 28.6	57.9 ± 1.44	5055 ± 179
Mean of improved crops (n=41)	1.91 ± 0.104	493 ± 24.5	57.6 ± 1.32	5231 ± 154
Mean difference	-0.43 ± 0.041	56 ± 11.5	-0.3 ± 0.87	176 ± 103
Probability difference is significant	<0.001	0.001	0.741	0.097

It is unclear from the datasets available to what extent that growers have taken the messages from this work on board and reduced nitrogen fertiliser applications. However, the large variation apparent in the Agrecalc dataset and additional anecdotal evidence would suggest that considerable over application of nitrogen continues. This is due to a number of factors including a perceived 'insurance' acquired from over application of nitrogen. This view was endorsed by consultation with stakeholders.

Application of uniform nitrogen rates across different fields and varieties is also common practice commercially as it simplifies the application, purchasing and management processes. But does not optimise use in every situation and will increase carbon emissions due to over application in some situations.

[16] Research reports on potato agronomy | AHDB and Potatoes grower collaboration project (2007-2014) | AHDB

The evidence that nitrogen is over applied by some growers and the wide variation in the Agrecalc data indicates that there are considerable opportunities for reductions in Nitrogen fertiliser applications without the need to compromise yield. Indeed, yield improvements can be expected where nitrogen fertiliser management is improved. Reductions in fertiliser use below those rates recommended will result in compromised yields. This is not economically sustainable and would result in an increased carbon footprint per tonne produced while reducing the footprint per hectare.

Targets

	Timescale	Target reduction	Actions
Stage 1	1-3 years	5%	Reduction of insurance application of nitrogen
Stage 2	4-6 years	10%	Continued reduction in nitrogen applications away from insurance application. Improved nitrogen management across different varieties and fields.
Stage 3	7-10 years	15%	Additional targeting of nitrogen applications using precision placements and split applications.

Evidence required.

Data on the optimum average nitrogen rate is available and proven to be effective. However, there is a requirement to convince growers that 'insurance' applications are not required.

New varieties are often poorly characterised and optimum agronomy regimes, including nitrogen application rates, are not necessarily known. Ensuring this information is available to growers would improve nitrogen use efficiency.

Recommended nitrogen rates rely upon average responses across a large number of situations. Individual circumstances might differ, and the understanding of these situations should be improved to provide optimum rates for individual situations.

Using varieties to reduce nitrogen fertiliser requirements

Current situation

Most varieties currently grown in Scotland for ware production are either group 2 or 3[17]. Group 1 varieties have a very high nitrogen requirement and should be avoided if reducing carbon footprints is a priority. Group 4 varieties are indeterminate, can produce a lot of foliage and are generally late maturing. These factors, for Scotland in particular, could impact negatively on carbon footprints and should be avoided if possible.

Reducing carbon footprints

A change in varieties towards those that require lower nitrogen applications to produce their optimum yield could have a significant impact on the carbon footprint of potato production.

For example, a change from group 2 varieties (E.g., Saxon or Osprey) to group 3 varieties (e.g., Maris Piper or Rooster) reduces the recommended nitrogen requirement by ca. 20%. Similar reductions can be made using a large number of less well known current varieties or those in development.

[17] tn651.pdf (sruc.ac.uk) and RB209 2021 Section 5 Potatoes | AHDB.

There are considerable barriers to the uptake of new varieties from the marketplace. However, for an individual grower a change of a proportion of their crop to a different Nitrogen grouping could have an important impact on the carbon footprint.

Targets

	Timescale	Target reduction in nitrogen use	Actions
Stage 1	1-3 years	3%	Implement a change in variety profile to deliver an overall reduction in determinacy rate of 1/8th (5 kg/ha ware).
Stage 2	4-6 years	6%	Implement a change in variety profile to deliver an overall reduction in determinacy rate of ¼ (10 kg/ha ware).
Stage 3	7-10 years	9%	Implement a change in variety profile to deliver an overall reduction in determinacy rate of 3/8th (15 kg/ha ware).

Evidence gaps and barriers to delivery

Experimental evidence is required for new varieties to ensure they are allocated to the correct nitrogen determinacy group.

Breeders have a great many target characteristics for new varieties in breeding programmes. Determinacy is poorly understood and not generally part of current breeding programmes.

Supply chain support for sustainable varieties requiring lower nitrogen inputs is required to ensure that growers are able to grow and market the reduced N requirement varieties.

Agronomy improvement

Current situation

The number of potato growers has declined over an extended period of time and within the Agrecalc data set there is considerable variation in farm size and yield (Table 6). Naturally those that remain in the sector are efficient and achieve yields such that they are able to remain in business.

For maincrop ware growers the yield varies from 39.5 t/ha to 61.0 t/ha with an average of 50.6 t/ha (Table 6). This large variation will be due to many complex interactions, including the land quality, varieties and markets as well as the agronomy and skill of the grower. As might be expected, seed and early growers produce lower yields than ware growers.

Carbon footprints of the potato crop (per tonne produced) is directly related to the yield, assuming the inputs remain the same. Improving yield of potato crops is therefore an effective way of reducing the carbon footprint.

Long term trends indicate that the average yield per hectare of potatoes has remained static at around 50 t/ha (GB data, Figure 2) since 2000.

Table 6: Number of hectares grown and yield of potato growers in the Agrecalc dataset.

		Farm data	
		ha	yield (t/ha)
Early	Average	62	33.0
	Standard dev	94.2	8.4
	Count	12	12
	90th Percentile	238.6	37.1
	10th percentile	8.4	24.1
Processing	Average	75.8	48.7
	Standard dev	102.4	5.5
	Count	13	13
	90th Percentile	204.0	55.0
	10th percentile	18.2	40.5
Ware	Average	66.5	50.6
	Standard dev	74.7	8.6
	Count	120	120
	90th Percentile	142.6	61.0
	10th percentile	8.0	39.5
Seed	Average	53.1	37.3
	Standard dev	48.5	6.8
	count	65	65
	90th Percentile	115.0	44.4
	10th percentile	10.3	27.6
All crops	**Average**	**62.7**	**45.4**
	Standard dev	**71.6**	**10.4**
	Count	**210**	**210**
	90th Percentile	**140.0**	**59.2**
	10th percentile	**9.0**	**31.3**

Reducing carbon footprints

Improvements in yield are required to reduce the carbon footprint of potatoes. This can be achieved, but will require genetic improvement of the varieties being grown and improvements to the agronomy of the potato crop. This includes improvement in nitrogen use efficiency discussed elsewhere which can be expected to deliver small yield improvements.

Targets[18]

Timescale		Target improvement from baseline	Actions
Stage 1	1-3 years	3.0% (1% per year)	Improved varieties and agronomy. Yield improvement from 45.4 to 46.7 t/ha.
Stage 2	4-6 years	Additional 3.0%	Improved varieties and agronomy. Yield improvement from 46.7 to 48.2 t/h.
Stage 3	7-10 years	Additional 4.0%	Improved varieties and agronomy. Yield improvement from 48.2 t/ha to 50.1 t/ha.

[18] McCain have a target yield improvement programme to deliver a targeted 1% yield improvement each year.

Evidence requirements and barriers to delivery

- Markets need ensure varieties with greater yield potential are available to growers.
- No independent programme of trials currently assesses yield potential of new varieties.
- In many instances the yield of a crop is determined by market factors. E.g., salad crops and seed are limited in yield to ensure that tubers are of the correct size.
- In these instances, yield is driven by the number of tubers produced and improvements have been made in this area.
- Yield improvements based on agronomic improvement and skill are reliant upon skilled agronomists with knowledge and experience to work with growers to improve their performance.

Roadmap part two

Introduction.

The roadmap outlined in Part 1 utilises the current knowledge base to deliver a significant reduction in the carbon footprint of potatoes. However, sustainability is a journey and further reduction will be required beyond the ten year timescale of part 1. These will rely upon new developments and innovations across a range of different technologies.

Target areas for development

Nitrogen use efficiency

The use of nitrogen fertiliser has been identified as the major contributor to the carbon footprint of potato production. The carbon footprint of nitrogen fertiliser use will have been reduced significantly if the steps in roadmap part 1 are implemented to their full extent. However, the footprint due to nitrogen fertiliser will remain the most significant contributor. As such, improved nitrogen use efficiency will continue to be required.

Improving the determination of the optimum crop requirement from an improved understanding of the crop physiology and determination of the residual nitrogen in soil can be utilised to improve resource use efficiency. Current standard practice is to make assumptions of nitrogen requirements based on past cropping with some small modifications for soil type and weather. These techniques result in best average applications rather than field and crop specific information.

Nitrogen is generally applied at planting or split between planting and the period around emergence (20-40 days after planting). The amount applied has little to do with the crop growth and precise timing of its needs. Precision application of fertiliser to match the requirements of the crop, which might vary across the field, would improve efficiency of use.

Nitrogen management can also be improved through measures designed to improve soil health and nitrogen fertility by the use of cover crops prior to planting potato crops. Understanding of the contributions to the nitrogen balance sheet from these sources would benefit N use efficiency.

Production of crops to produce their own nitrogen (as occurs in legumes) can be considered for future breeding programmes.

Nitrogen is the major contributor to the carbon footprint of the potato crop. However smaller contributions from the use of Phosphate and Potash fertiliser need to be considered and the efficiency of product use improved.

Alternative fuels

Diesel use is the second most important contributor to the carbon footprint and after all steps in the roadmap are implemented, will remain an important contributor.

Potatoes are currently grown in a ridge and bed system which involves considerable soil cultivation and movement. It can be assumed that the act of harvesting of an underground tuber will always involve lifting the soil and separating tubers from the soil. Thus, both planting and harvesting by their nature are energy intensive operations. Replacement of diesel with alternative fuels may ultimately reduce the carbon footprint of this operation.

Alternative fuels are out with the scope of this project. However, we can assume that electrical (battery) fuelled machines will be too heavy to operate large scale field operations. Developments in other sectors (haulage) can be assumed to be applied to agriculture as developments occur.

Genetic potential

Improved varieties are a key element of the drive to reduce carbon footprints in potato production. Developments in breeding can be focussed on many of the elements described under 'Improved yield potential', 'Improved disease resistance' and 'Storage efficiency'.

Improvement in yield potential

The yield of potatoes has been static over recent decades. In Scotland, long days combined with a lengthened growing season due to climate change provides an opportunity for high yields. As outlined elsewhere in this report, improvements to yield while utilising similar resource inputs can be a major contributor to reducing the carbon footprint of production.

Yield improvements can be achieved through either agronomic or genetic improvement (or both combined). Routes towards agronomic improvement are many and cannot be considered in detail here, but could include.

- Improved seed management and physiology
- Improved soil management and health
- Utilisation of crop and plant physiology knowledge to maximise yield potential.
- Improved water management of the crop, including water use efficient crop varieties
- Improved nitrogen use efficiency, especially maincrop and processing varieties, including better understanding of options for capturing nitrogen left in crop residues
- Improved disease and pest prediction and control, particularly of those that affecting the roots of potato plants.

Precision farming

The basis of precision farming is the application of variable amounts of resources as required to areas of fields (or ultimately individual plants) to ensure their most efficient use, such as fertiliser, water or pesticides.

Developments in precision agriculture can be applied to potatoes. Careful analysis of the carbon footprint implications should be made, but many applications will result in reduced footprints and improved average yields across field.

Understanding of the precise physiological needs of potato plants and the requirement for measured inputs is required to take this forward alongside the appropriate technology to deliver the inputs.

Improved disease resistance

Pesticide application is currently essential for the production of potato crops. Pesticides themselves are known to have relatively small footprints in their production. However, application can be a driver of carbon footprints. The most significant element is the application of blight fungicides to crops on a generally weekly basis through the growing season. Fuel is used to make this application and although improvements have been made as the sprayers become larger (width sprayed) and control technologies reduce application to non-cropped areas, the use of energy in this operation remains significant.

The use of genetic resistance to pests and diseases reduces the need for pesticides and the fuel needed to apply them. This should be combined with decision support systems for predicting when applications are needed and to avoid redundant spraying. Future breeding developments should ensure high levels of resistance to blight.

Storage efficiency

Storage of potatoes, a seasonally produced crop with a year round requirement, is an essential element of the potato supply chain. The alternative is to import potatoes from other locations with climates that enable production during different times of the year. Generally, the movement of potatoes, a bulky product, containing around 20% dry matter is only economically viable to supply specific quality requirements for short periods of time. The carbon footprint analysis of imported potatoes has not been included in this exercise although it can be assumed to be a significant contributor to the equation.

Storage efficiency is determined by (a) the mechanical and thermodynamic efficiency of the cooling mechanism and the structure within which the potato is being stored and (b) the temperature and ventilation requirements of the potato crop to ensure quality is maintained.

Technical developments in the development of improved insulation and mechanical cooling of potato stores will deliver, over time, improved store efficiency. The utilisation of renewable energy generated on site or by the national grid will also influence the footprint from potato storage. However, it will remain the case that making best use of energy, is essential.

Genetic improvement and physiological understanding of the stored potato crop can in future deliver improved results and permit a reduction in energy use in storage. Examples include.

- Improving the understanding of and triggers to dormancy break.
- Genetic improvement in varieties to improve dormancy and thereby reduce the need for cooling.
- Physiological understanding to permit the development of new sprout suppressants.
- Development of varieties which retain processing quality at temperatures which can be maintained using minimum energy requirements (ambient air ventilation).

Improved soil management

Soil management requires a rotational and holistic approach to improve and develop. Potatoes are a single element of the rotation and as discussed in the report are most often grown on rented land out with the control of the potato grower for a considerable part of the rotational cycle.

The potato crop can benefit directly from improved soil management by reducing fertiliser requirements, requiring less mechanical cultivation and improving yield potential. However, it is apparent that reduced tillage systems and other elements of 'regenerative' agriculture are at odds with the current cultivation requirements of the potato crop. Development of innovative cultivation systems which ensure maintenance of 'soil quality' with reduced greenhouse gas emissions during potato production should be investigated to improve this aspect of production.

Improved seed quality

Seed is the building block on which all potato crops are produced and seed quality is essential to maximise yield potential and ensure a high quality product. The seed potato sector in Scotland, which supplies over 70% of the UK seed potato requirements as well as being exported to many countries throughout the world, is testament to the demand for quality.

Improvements in seed quality have been made over many years. However further improvements can be made to ensure developments continue. Understanding and forecasting dormancy and sprouting of seed would enable improvements in agronomy and improve the utilisation of resources.

Control of seed borne diseases through the implementation of Integrated Pest Management techniques including use of genetic resistance, targeted pesticides, improved store management and soil diagnostics would ensure maximum yield with minimum resource requirements.

Reduced waste

Waste in potato production is complex as only a very small portion of the potato crop is wasted in the sense that it is unutilised. However, within supply chains, a considerable proportion of the crop can fail to meet the requirements for the intended market. These 'waste' potatoes are then used for less profitable markets. The proportion of crops (or part of crops) that fail to reach the requirements is highly variable and dependent on both the potato quality and market conditions at the time.

Less profitable markets include, 'value' packs, lower grade processing uses, bag markets, starch, cattle feed, biogas production.

Improvements in the proportion of crops meeting the intended market specifications would ensure improved profitability and reduce the carbon footprint of the supply chain through reduced transport and handling.

Waste reduction would be achieved through a combination of improved crop quality, agronomy, genetics, storage and disease control.

Current activity supporting reduction in carbon footprint of potatoes at SRUC and JHI

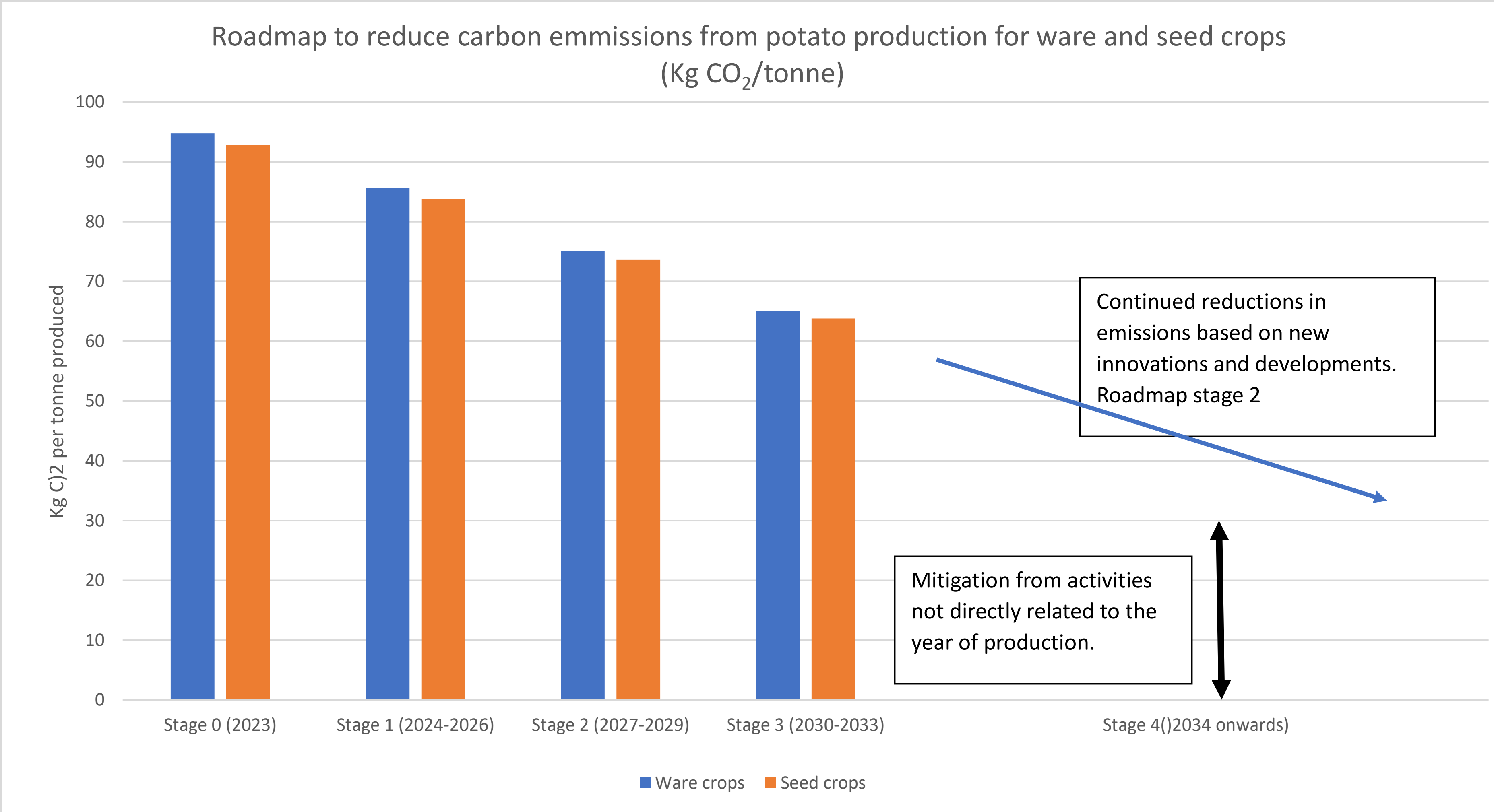
	SRUC	**JHI**
Nitrogen use efficiency	Advise to growers on correct nitrogen management. https://www.sruc.ac.uk/business-services/sac-consulting/agricultural-production/technical-notes/#fertiliser	Studies of varietal differences in P use efficiency traits might inform studies of traits for N use efficiency: https://link.springer.com/article/10.1007/s11104-018-3776-5
Water use efficiency		Drought tolerance associated with varietal differences in stolon traits: https://link.springer.com/article/10.1007/s11104-014-2029-5#Sec2
Alternative fuels		
Genetic potential		Genetics and Breeding | Potato@Hutton The James Hutton Institute
Improvement in yield potential	Advise to both seed and ware growers and grower groups on agronomy to improve seed health.	Stress tolerant potato genotypes: Abiotic Stress | Potato@Hutton The James Hutton Institute Planned future work in a new PhD studentship: https://www.ctp-sai.org/projects-for-2024-1/understanding-genotypic-variation-in-potato-hybrid-populations-of-root-morphological-and-anatomical-characteristics-%E2%80%93-identifying-traits-for-a-climate-resilient-potato.-
Precision farming	Ground keeper control in collaboration with others Work Package 6 - Groundkeeper Control | Potato Cyst Nematode Hub (pcnhub.ac.uk)	
Improved disease and pest resistance	Support for growers producing new and improved varieties. Delivery of KE events to support new variety development. Barnyards Open Day 2022 - Trial	Developing universally transferrable markers for commercial disease resistance breeding | Potato@Hutton The James Hutton Institute Fight Against Blight | The James Hutton

	Results Summary | Potato Cyst Nematode Hub (pcnhub.ac.uk)	Institute
Storage efficiency	Crop Storage and Post-Harvest Solutions - CHAP (chap-solutions.co.uk) Delivery of stare management courses. Advise to growers and grower groups on store management.	Understanding the tuber life cycle | Potato@Hutton The James Hutton Institute Crop Storage and Post-Harvest Solutions - CHAP (chap-solutions.co.uk)
Improved soil management		Balruddery Farm Centre for Sustainable Cropping: https://csc.hutton.ac.uk/agronomy.asp
Improved seed quality	Advise to both seed and ware growers and grower groups on agronomy to improve seed health. Delivery of diagnostic services in support of production.	Maintenance of insect cultures for IPM research: https://ics.hutton.ac.uk/hutton-collections/#/pests
Reduced waste	Advise to both seed and ware growers and grower groups on agronomy to reduce waste.	Potato tuber greening | Potato@Hutton The James Hutton Institute

Roadmap for reducing greenhouse gas emissions from Scottish potato crops.

Stage	Actions	Effect on carbon footprint	Carbon footprint (Kg CO2 per tonne (Ware)	Carbon footprint (Kg CO2 per tonne (Seed)
Stage 0 (year 0)				
	Benchmark carbon footprint using a carbon calculator tool.		94.8	92.8
	Determine target areas for action			
Stage 1 (years 1-3)				
10% reduction in diesel use	High users will be able to make simple efficiencies	-2.2%		
10% improvement in store efficiency	Audit of store management and energy requirements. High users will be able to make simple efficiencies to store leakage and management.	-1.0%		
5% reduction in nitrogen use	Reduction of insurance application of nitrogen	-2.7%		
3% less nitrogen applied (5kg)	Implement a change in variety profile to deliver an overall reduction in determinacy rate of 1/8 (5kg/ha ware).	-1.7%		
Total reduction		-7.6%	88.2	86.3
Improvement in yield of 3%			85.6	83.8
	Total reduction in carbon footprint		**10.70%**	**9.60%**
Stage 2 (years 4-6)				
20% reduction in diesel use	Improvements in efficiencies combined with improvements in cultivation practices	-4.5%		

20% improvement in store efficiency	Investment in store modification to improve airflow and store management. Improved insulation and other moderate investments.	-2.0%		
10% reduction in nitrogen use	Continued reduction in nitrogen applications away from insurance application. Improved nitrogen management across different varieties and fields.	-5.8%		
6 % less nitrogen applied (10 kg)	Implement a change in variety profile to deliver an overall reduction in determinacy rate of ¼ (10kg/ha ware).	-3.5%		
Total reduction		-15.8%	79.6	78.1
Additional Improvement in yield of 3%			75.1	73.7
	Total reduction in carbon footprint		**-20.7%**	**-20.5%**
Stage 3 (years 7-10)				
30% reduction in diesel use	Achieved through improved practices and changes to land management and choice.	-6.7%		
30% improvement in store efficiency	Improve storage efficiency though new storage estate.	-3.0%		
15% reduction in nitrogen use	Additional targeting of nitrogen applications.	-8.7%		
9% less nitrogen applied (15kg)	Implement a change in variety profile to deliver an overall reduction in determinacy rate of 3/8 (15 kg/ha ware).	-5.2%		
Total reduction		-23.6%	72.4	70.9
Additional improvement of yield of 4%			65.1	63.8
	Total reduction in carbon footprint		**-31.3%**	**-31.2%**



Roadmap to reduce carbon emmissions from potato production for ware and seed crops
(Kg CO_2/tonne)
Kg C)2 per tonne produced
100
90
80
70
60
50
40
30
20
10
0
Continued reductions in emissions based on new innovations and developments. Roadmap stage 2
Mitigation from activities not directly related to the year of production.
Stage 0 (2023)
Stage 1 (2024-2026)
Stage 2 (2027-2029)
Stage 3 (2030-2033)
Stage 4()2034 onwards)
Ware crops
Seed crops

Appendix

Table A1. Direct Carbon emissions (kg CO_2) from fuel for different crop types

Crop type		Diesel emissions			Electricity emissions			other fuels emissions			Total direct fuel emissions		
		Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne
Early potatoes	Total	776376	11653	379.3	206246	1985	68.5	261102	1284	37.0	1252158	14952	485.6
	Average	64698	971	32	17187	165	6	21758	107	3	104346	1246	40
	Standard dev	102997	408	16.5	35056	173	6.6	66505	230	6.3	196665	569	21.1
	Count	12	12	12	12	12	12	12	12	12	12	12	12
	90th Percentile	199546	1370	42.9	84525	371	10.3	6976	97	3.3	294417	2052	67.3
	10th percentile	6026	626	17.4	0	0	0.0	0	0	0.0	7474	744	25.2
Maincrop processing potatoes	Total	974507	14499	306.6	538610	4028	82.4	154544	3032	62.4	1671878	21651	453.2
	Average	74962	1115	23.6	41432	310	6.3	11888	233	4.8	128606	1665	34.9
	Standard dev	87316	898	18.6	102016	317	6.5	31943	702	14.2	190809	1788	36.3
	Count	13	13	13	13	13	13	13	13	13	13	13	13
	90th Percentile	186746	1846	40.7	44745	891	17.9	16840	89	2.3	327321	2174	47.9
	10th percentile	9340	324	5.8	2280	113	2.2	137	4	0.1	14894	547	9.9
Maincrop ware potatoes	Total	8581625	124792	2518.9	3377865	54389	1113.2	938956	10228	216.2	12950240	189442	3849.0
	Average	71279	1031	20.8	27916	449	9.2	7760	85	1.8	107027	1566	31.8
	Standard dev	85517	535	10.8	42984	650	14.9	31566	151	3.5	132658	856	19.8
	Count	121	121	121	121	121	121	121	121	121	121	121	121
	90th Percentile	173097	1534	32.4	66071	814	16.4	10520	191	3.7	254863	2483	50.6
	10th percentile	4896	524	10.1	0	0	0.0	0	0	0.0	7626	773	16.6
Seed potatoes	Total	3682736	64701	1822.0	806415	16799	464.8	236486	4593	127.0	4725740	86095	2413.9
	Average	56657	995	28.0	12406	258	7.2	3638	71	2.0	72704	1325	37.1
	Standard dev	84157	536	17.0	13995	298	8.2	5836	73	2.0	94493	670	20.8
	count	65	65	65	65	65	65	65	65	65	65	65	65
	90th Percentile	113708	1495	45.7	31865	483	13.5	7215	165	4.5	150084	2000	59.8
	10th percentile	6188	416	9.7	30	3	0.1	0	0	0.0	9212	474	13.8
All crops	**Total**	**14015244**	**214656**	**5007.0**	**4893456**	**76382**	**1712.5**	**1588226**	**19072**	**441.4**	**20518321**	**310267**	**7164.3**
	Average	**66739**	**1022**	**23.8**	**23302**	**364**	**8.2**	**7563**	**91**	**2.1**	**97706**	**1477**	**34.1**
	Standard dev	**86771**	**560**	**14.4**	**43709**	**536**	**12.5**	**30298**	**223**	**4.9**	**132934**	**891**	**21.8**
	Count	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**
	90th Percentile	**162332**	**1534**	**41.9**	**55605**	**733**	**16.3**	**10287**	**179**	**4.1**	**237224**	**2349**	**56.0**
	10th percentile	**5386**	**469**	**9.7**	**0**	**0**	**0.0**	**0**	**0**	**0.0**	**8434**	**701**	**15.5**

Table A2(a). Indirect Carbon emissions (kg CO_2) for different crop types (Fertiliser, Lime, Pesticides and Waste)

Crop type		Fertiliser indirect emissions			Lime indirect emissions			Pesticide indirect emissions			Waste emissions		
		Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne
Early potatoes	Total	913452	15274	487.9	37003	196	6.4	4813	72	2.3	3244	20	0.6
	Average	76121	1273	41	3084	16	1	401	6	0	270	2	0
	Standard dev	111745	476	19.8	10121	40	1.2	635	1	0.0	832	3	0.1
	Count	12	12	12	12	12	12	12	12	12	12	12	12
	90th Percentile	238643	1834	53.9	318	49	2.3	1595	7	0.2	167	6	0.2
	10th percentile	6849	805	22.2	0	0	0.0	41	5	0.1	0	0	0.0
Maincrop processing potatoes	Total	1842636	24558	511.3	0	0	0.0	14415	101	2.1	1541	35	0.7
	Average	141741	1889	39.3	0	0	0.0	1109	8	0.2	119	3	0.1
	Standard dev	186838	228	6.9	0	0	0.0	2773	6	0.1	402	9	0.2
	Count	13	13	13	13	13	13	13	13	13	13	13	13
	90th Percentile	430739	2105	49.9	0	0	0.0	1332	7	0.2	11	1	0.0
	10th percentile	34296	1641	34.5	0	0	0.0	100	5	0.1	0	0	0.0
Maincrop ware potatoes	Total	14505988	204292	4091.0	549255	10869	205.4	48792	750	15.2	6004	162	3.0
	Average	120883	1702	34.1	4577	91	1.7	407	6	0.1	50	1	0.0
	Standard dev	133641	666	13.7	25784	423	8.0	492	4	0.1	281	6	0.1
	Count	120	120	120	120	120	120	120	120	120	120	120	120
	90th Percentile	291902	2455	48.2	2011	131	2.4	874	7	0.2	84	2	0.0
	10th percentile	5610	955	18.4	0	0	0.0	16	3	0.1	0	0	0.0
Seed potatoes	Total	4551787	83251	2283.2	121241	4537	111.5	26166	515	14.7	1430	45	1.3
	Average	70027	1281	35.1	1865	70	1.7	403	8	0.2	22	1	0.0
	Standard dev	66091	428	11.2	10173	373	8.8	498	7	0.2	46	2	0.1
	count	65	65	65	65	65	65	65	65	65	65	65	65
	90th Percentile	165469	1589	49.0	110	3	0.1	827	7	0.2	67	2	0.0
	10th percentile	11220	908	23.0	0	0	0.0	63	6	0.1	0	0	0.0
All crops	**Total**	**21813863**	**327376**	**7373.4**	**707499**	**15602**	**323.3**	**94186**	**1438**	**34.2**	**12219**	**262**	**5.7**
	Average	**103876**	**1559**	**35.1**	**3369**	**74**	**1.5**	**449**	**7**	**0.2**	**58**	**1**	**0.0**
	Standard dev	**122821**	**611**	**13.2**	**20494**	**382**	**7.8**	**862**	**5**	**0.2**	**314**	**5**	**0.1**
	Count	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**
	90th Percentile	**265762**	**2330**	**51.9**	**706**	**55**	**1.6**	**892**	**7**	**0.2**	**84**	**2**	**0.0**
	10th percentile	**7984**	**913**	**20.6**	**0**	**0**	**0.0**	**38**	**5**	**0.1**	**0**	**0**	**0.0**

Table A2(b). Indirect Carbon emissions (kg) for different crop types (Transport and totals)

Crop type		Transport emissions			Total indirect emissions			Total energy use (Direct and indirect)		
		Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne
Early potatoes	Total	82951	295	8.1	1041462	15857	505.3	2293620	30809	990.9
	Average	6913	25	1	86789	1321	42	191135	2567	83
	Standard dev	22926	82	2.2	132994	461	19.2	319377	635	26.2
	Count	12	12	12	12	12	12	12	12	12
	90th Percentile	0	0	0.0	317731	1843	54.1	673828	3271	115.3
	10th percentile	0	0	0.0	6892	811	22.4	13297	1873	48.6
Maincrop processing potatoes	Total	41475	912	18.4	1900067	25605	532.6	3571944	47257	985.8
	Average	3190	70	1.4	146159	1970	41.0	274765	3635	75.8
	Standard dev	11052	243	4.9	188409	299	7.7	366309	1970	40.7
	Count	13	13	13	13	13	13	13	13	13
	90th Percentile	0	0	0.0	432071	2333	53.4	690282	3826	85.4
	10th percentile	0	0	0.0	34414	1651	34.9	53151	2516	45.8
Maincrop ware potatoes	Total	95585	651	14.9	15205625	216726	4329.6	28074170	404294	8141.1
	Average	797	5	0.1	126714	1806	36.1	233951	3369	67.8
	Standard dev	7555	31	0.7	141252	784	15.6	260797	1203	26.4
	Count	120	120	120	120	120	120	120	120	120
	90th Percentile	0	0	0.0	296417	2562	55.0	562679	4600	96.3
	10th percentile	0	0	0.0	5627	987	19.7	19334	2016	37.9
Seed potatoes	Total	5184	234	9.4	4705809	88583	2420.1	9431549	174678	4834.0
	Average	80	4	0.1	72397	1363	37.2	145101	2687	74.4
	Standard dev	541	23	0.9	66790	565	13.8	150085	807	25.7
	count	65	65	65	65	65	65	65	65	65
	90th Percentile	0	0	0.0	169935	1633	51.1	276088	3509	108.5
	10th percentile	0	0	0.0	11754	954	24.7	21706	1808	46.5
All crops	**Total**	**225196**	**2092**	**50.8**	**22852963**	**346771**	**7787.5**	**43371284**	**657038**	**14951.8**
	Average	**1072**	**10**	**0.2**	**108824**	**1651**	**37.1**	**206530**	**3129**	**71.2**
	Standard dev	**8537**	**71**	**1.6**	**129220**	**721**	**15.0**	**248742**	**1191**	**27.6**
	Count	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**
	90th Percentile	**0**	**0**	**0**	**274057**	**2463**	**53.9**	**533570**	**4490**	**103.4**
	10th percentile	**0**	**0**	**0**	**8041**	**955**	**21.8**	**20729**	**1925**	**43.5**

Table A3. Carbon emission (kg) equivalent from nitrous oxide (fertiliser and residues)

Crop type		Nitrous oxide (Cequ) emissions from fertiliser			Nitrous oxide (C equ) emissions from residues			Total nitrous oxides		
		Total	Per ha	Per tonne	Total	Per ha	Per tonne	Total	Per ha	Per tonne
Early potatoes	Total	419339	8011	253.8	164753	2331	75.3	584092	10342	329.2
	Average	34945	668	21	13729	194	6	48674	862	27
	Standard dev	43910	496	18.2	26254	87	3.4	68611	507	19.1
	Count	12	12	12	12	12	12	12	12	12
	90th Percentile	98570	1467	28.6	35702	306	10.5	134272	1679	32.7
	10th percentile	2417	283	9.6	1564	72	2.6	4968	501	14.5
Maincrop processing potatoes	Total	964867	15778	342.2	271532	4275	86.9	1236399	20052	429.1
	Average	74221	1214	26.3	20887	329	6.7	95108	1542	33.0
	Standard dev	80809	634	16.1	23717	122	2.1	103377	623	16.1
	Count	13	13	13	13	13	13	13	13	13
	90th Percentile	198417	2046	42.9	60256	510	9.3	265443	2420	50.8
	10th percentile	15546	600	10.9	6331	188	4.3	24542	824	17.2
Maincrop ware potatoes	Total	8534456	116700	2357.1	2162670	32372	643.4	10697126	149072	3000.4
	Average	71120	972	19.6	18022	270	5.4	89143	1242	25.0
	Standard dev	100544	600	12.9	25264	136	2.6	119262	629	13.7
	Count	120	120	120	120	120	120	120	120	120
	90th Percentile	196513	1711	33.0	40408	505	9.2	245806	1907	38.1
	10th percentile	3332	361	7.2	978	146	2.6	4646	588	11.9
Seed potatoes	Total	1892037	35663	998.6	624646	12166	330.4	2516683	47830	1329.0
	Average	29108	549	15.4	9610	187	5.1	38718	736	20.4
	Standard dev	29622	285	8.9	10920	107	3.2	37329	306	9.8
	count	65	65	65	65	65	65	65	65	65
	90th Percentile	66584	974	26.2	19586	322	7.4	99715	1257	33.1
	10th percentile	3499	251	6.2	1158	101	2.6	5577	427	11.0
All crops	**Total**	**11810699**	**176152**	**3951.7**	**3223601**	**51144**	**1136.0**	**15034300**	**227296**	**5087.8**
	Average	**56241**	**839**	**18.8**	**15350**	**244**	**5.4**	**71592**	**1082**	**24.2**
	Standard dev	**83444**	**562**	**12.8**	**22185**	**132**	**2.8**	**100321**	**601**	**13.6**
	Count	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**	**210**
	90th Percentile	**128365**	**1551**	**32.9**	**34665**	**430**	**9.3**	**166590**	**1815**	**39.3**
	10th percentile	**3351**	**303**	**7.2**	**1230**	**123**	**2.6**	**5264**	**485**	**11.6**

Table A4. Total Carbon emission (kg) equivalent from potato production and farm summary data

Crop type		Total emission from potato production			Farm data		
		Total	Per ha	Per tonne	Total t	ha	yield (t/ha)
Early potatoes	Total	2877712	41151	1320.1	27183	743.5	395.0
	Average	239809	3429	110	2265	62	33
	Standard dev	379919	903	39.1	3496	94.2	8.4
	Count	12	12	12	12	12	12
	90th Percentile	892879	4316	138.9	8904	238.6	37.1
	10th percentile	19215	2332	76.9	210	8.4	24.1
Maincrop processing potatoes	Total	4808343	67309	1414.9	45654	985.3	633.4
	Average	369873	5178	108.8	3512	75.8	48.7
	Standard dev	457940	1913	42.8	4639	102.4	5.5
	Count	13	13	13	13	13	13
	90th Percentile	981923	5743	146.9	8175	204.0	55.0
	10th percentile	77419	3628	66.0	864	18.2	40.5
Maincrop ware potatoes	Total	38771296	553366	11141.6	415702	7986.0	6072.0
	Average	323094	4611	92.8	3464	66.5	50.6
	Standard dev	356155	1563	33.5	3835	74.7	8.6
	Count	120	120	120	120	120	120
	90th Percentile	747863	6273	130.5	7408	142.6	61.0
	10th percentile	25410	2762	53.9	314	8.0	39.5
Seed potatoes	Total	11948232	222507	6163.0	131799	3451.0	2425.8
	Average	183819	3423	94.8	2028	53.1	37.3
	Standard dev	183856	947	30.7	1940	48.5	6.8
	count	65	65	65	65	65	65
	90th Percentile	377497	4480	136.6	4514	115.0	44.4
	10th percentile	27661	2478	61.3	379	10.3	27.6
All crops	**Total**	**58405584**	**884334**	**20039.5**	**620337**	**13165.9**	**9526.2**
	Average	**278122**	**4211**	**95.4**	**2954**	**62.7**	**45.4**
	Standard dev	**329681**	**1524**	**34.1**	**3473**	**71.6**	**10.4**
	Count	**210**	**210**	**210**	**210**	**210**	**210**
	90th Percentile	**709929**	**5919**	**135.6**	**6989.0**	**140.0**	**59.2**
	10th percentile	**26942**	**2571**	**56.7**	**320.0**	**9.0**	**31.3**

Figure A1: Scatter chart of Carbon emissions from diesel use per hectare related to the total emissions per tonne produced.

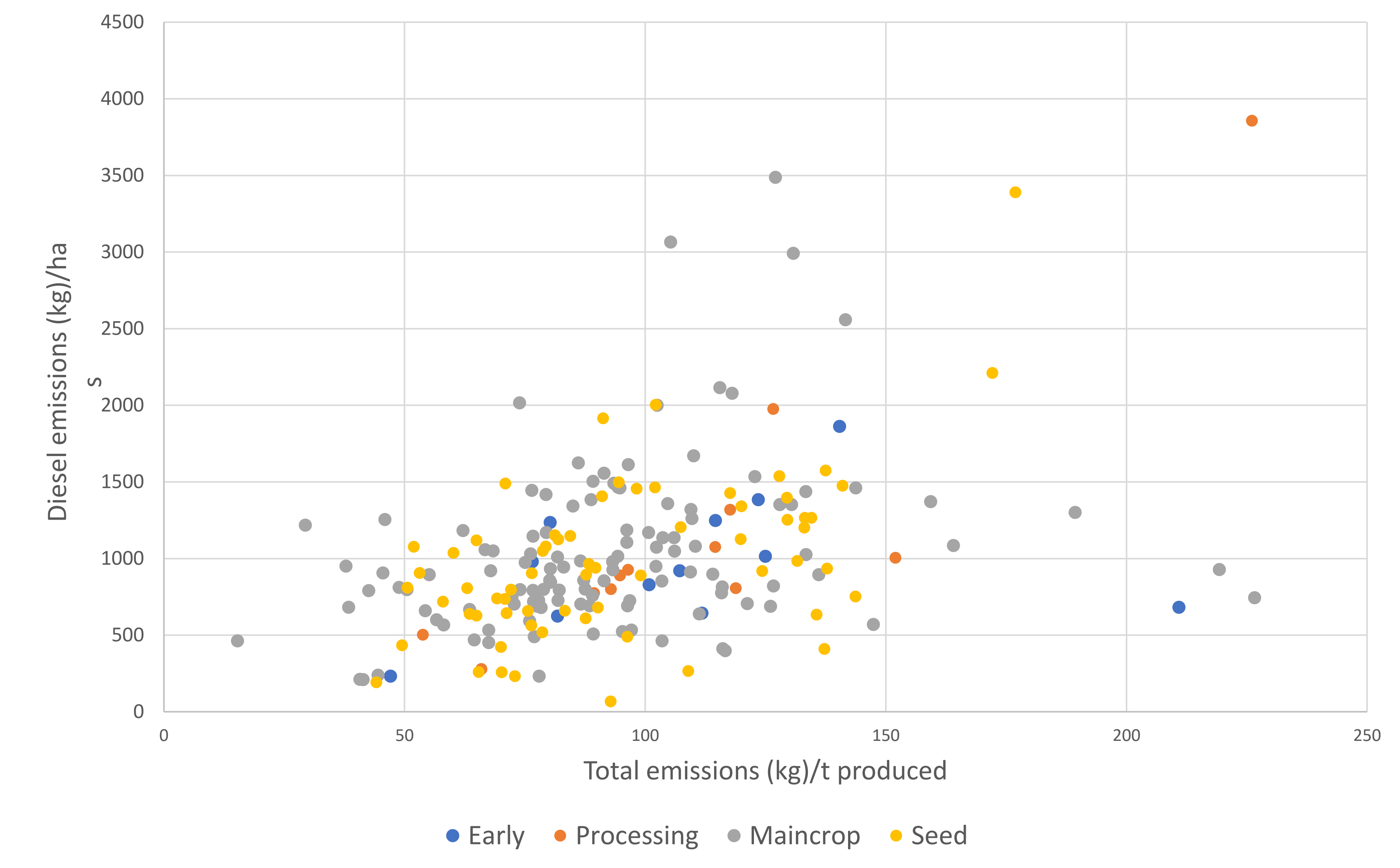


Figure A2: Scatter chart of indirect Carbon emissions from fertiliser use per hectare related to the total emissions per tonne produced.

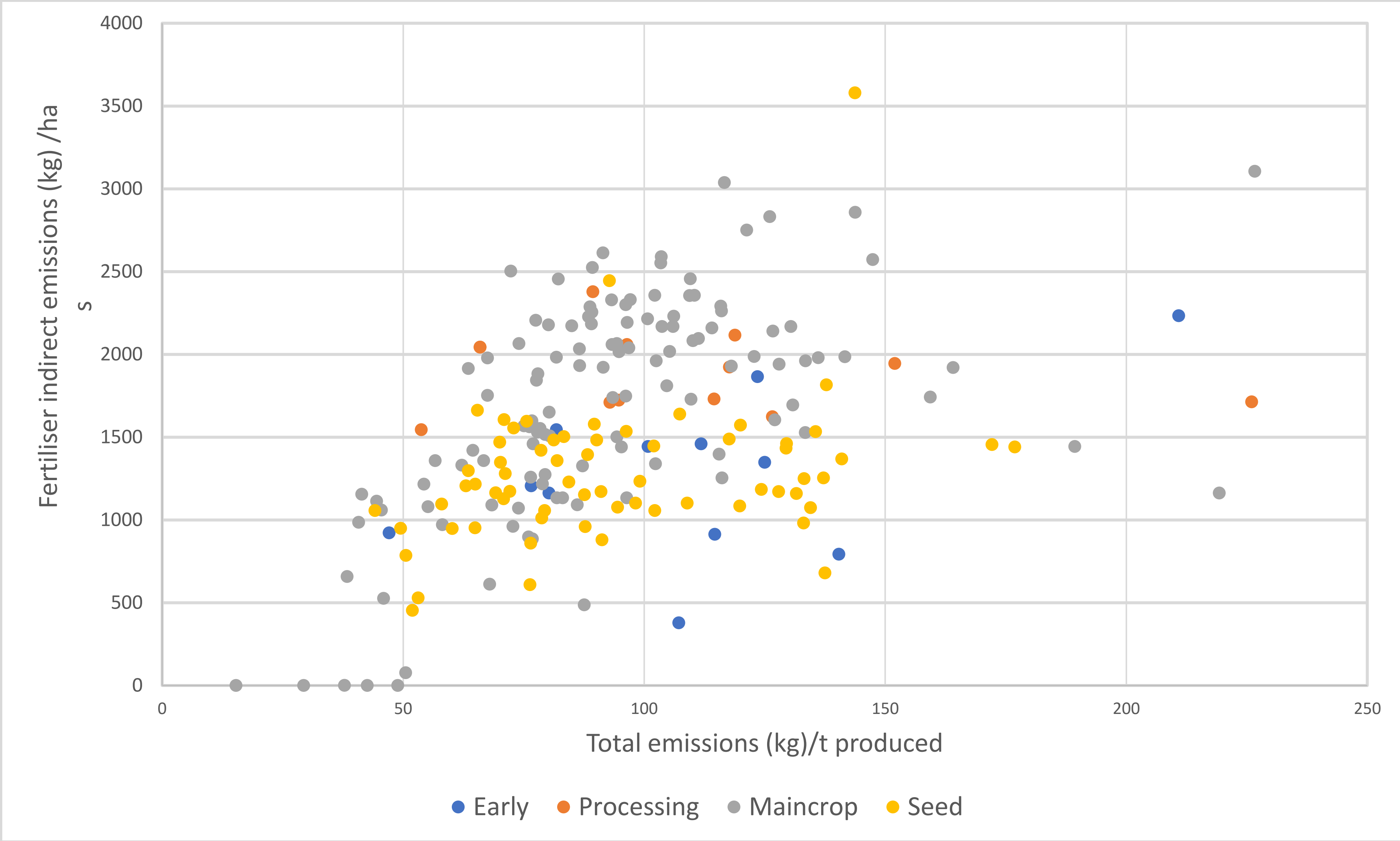


Figure A3: Scatter chart of indirect Carbon emissions from crop protection use per hectare related to the total emissions per tonne produced.

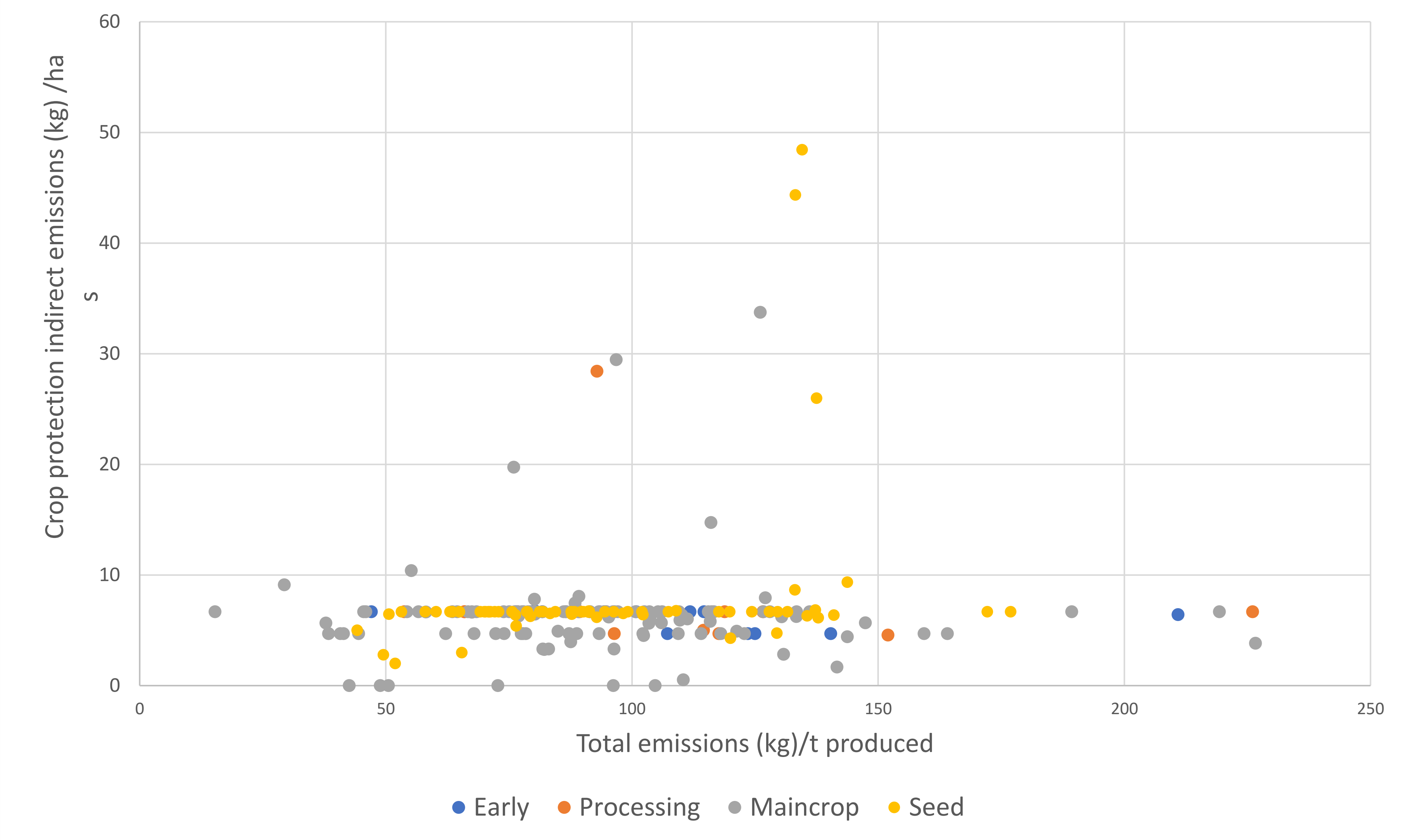


Figure A4: Scatter chart of Nitrous oxide Carbon emission equivalent per hectare related to the total emissions per tonne produced.

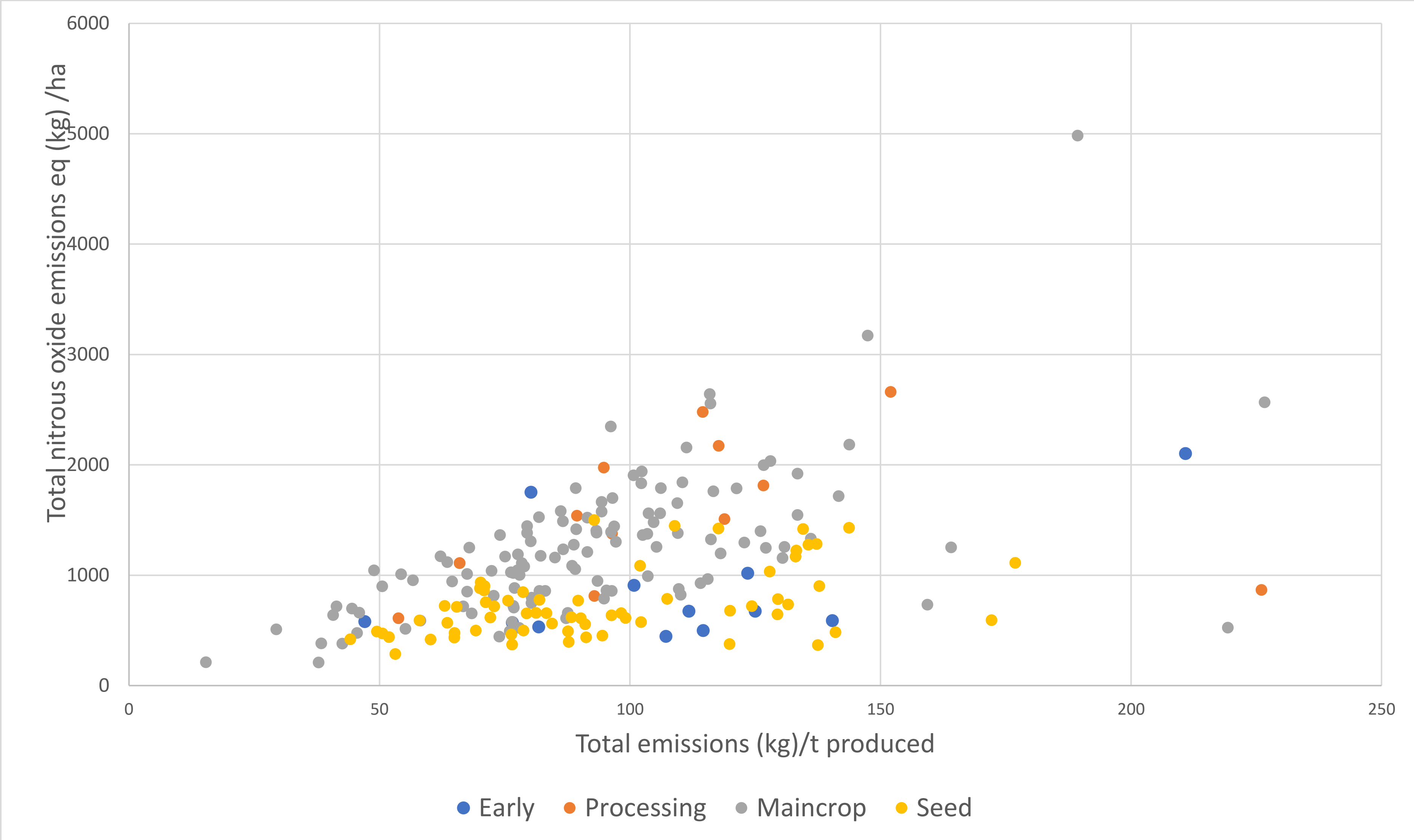


Figure A5: Scatter chart of total Carbon emissions (equivalent) per hectare (direct and indirect) related to the total emissions per tonne produced.

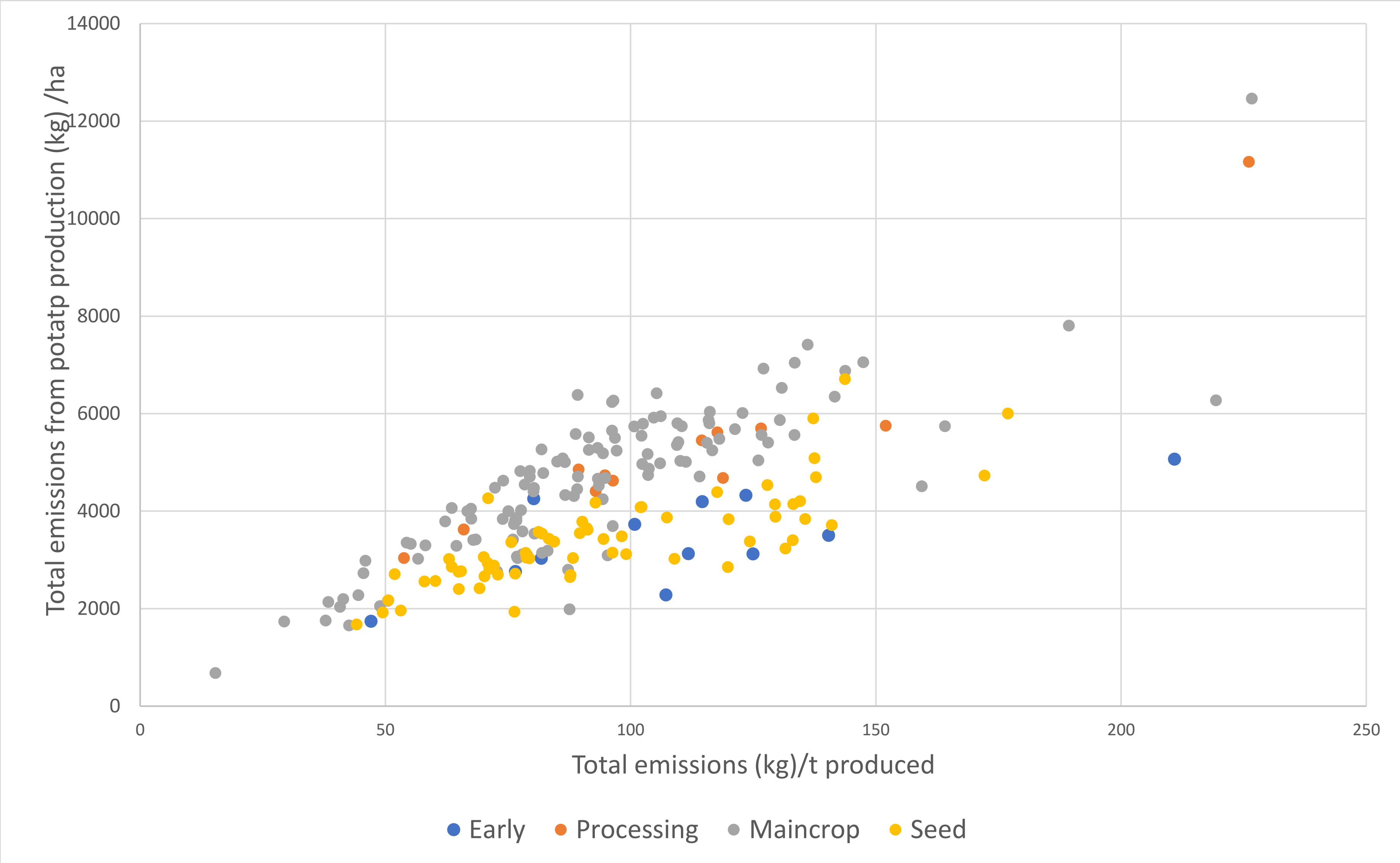


Figure A6: Scatter chart of area grown (ha) related to the total emissions per tonne produced.

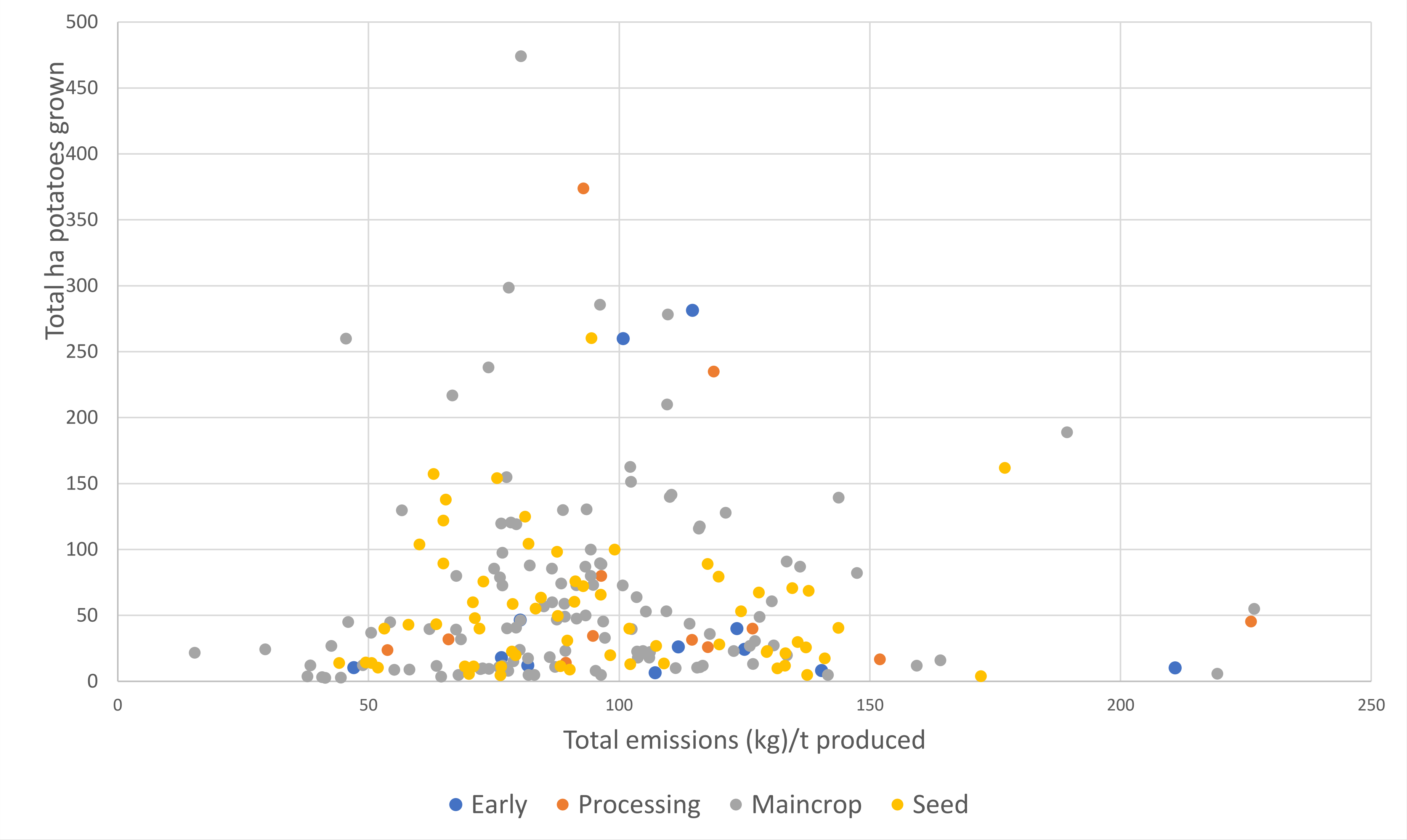


Figure A7: Scatter chart of yield (tonnes per ha) related to the total emissions per tonne produced.

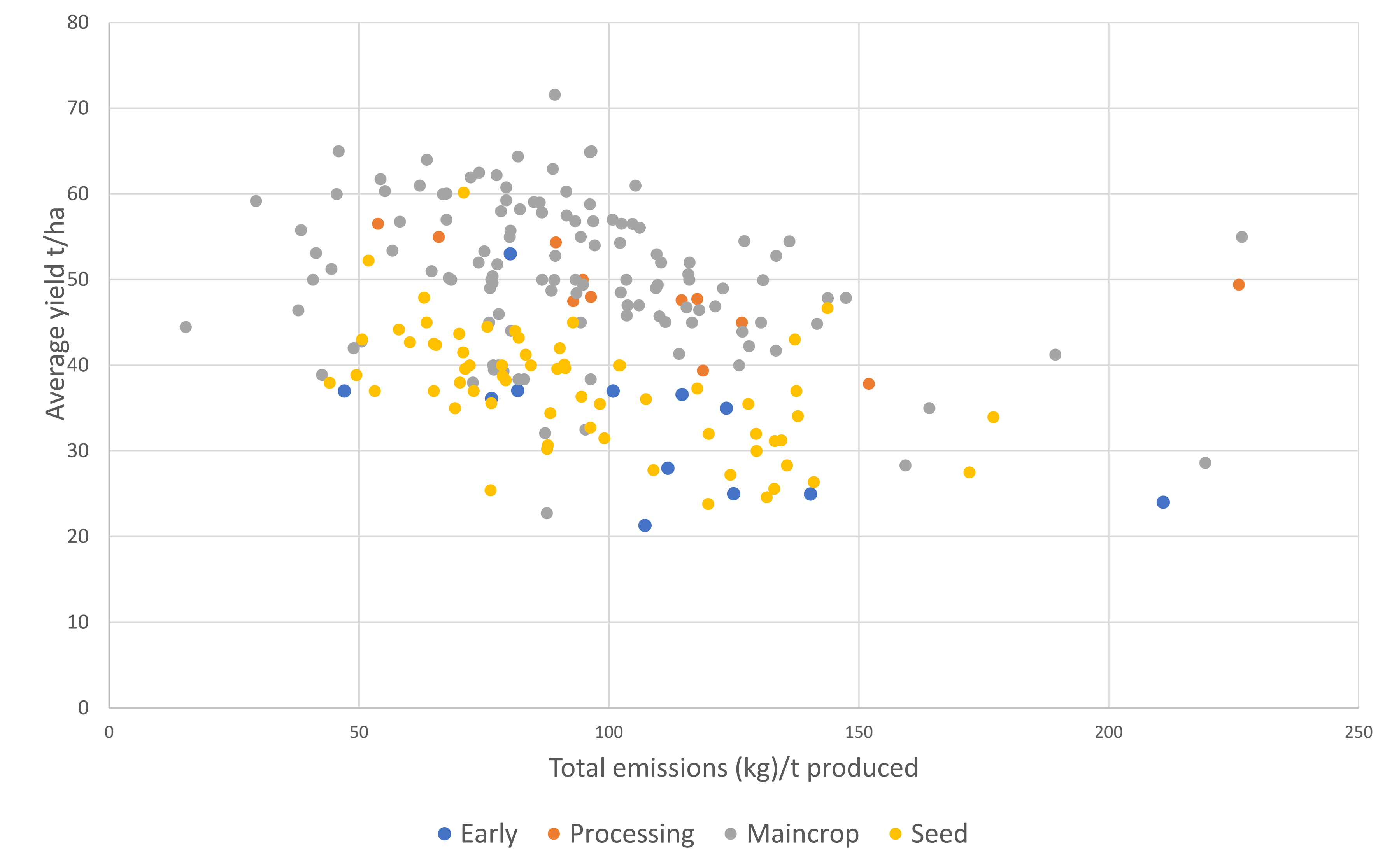


Table A5: Correlation coefficients for against the total emissions per tonne of variables within the Agrecalc dataset

Correlation with Emissions per tonne	Correlation coefficient r^2	Correlation coefficient r^3
	Per ha	Per tonne
Diesel emissions	0.19	0.32
Electricity emissions	0.14	0.19
other fuels emissions	0.08	0.10
Total direct fuel emissions	0.33	0.48
Fertiliser indirect emissions	0.18	0.45
Pesticide indirect emissions per tonne	0.02	0.05
Total indirect emissions	0.21	0.48
Total energy use (Direct and indirect)	0.50	0.85
Nitrous oxide eq emissions fertiliser	0.27	0.41
Nitrous oxides eq emissions residues	0.00	0.02
Total nitrous oxides	0.22	0.40
Total tonnes produced	0.00	
Ha grown	0.00	
Yield per ha	0.11	