



Title	Estimating the current area of European tillage systems occupied by tramlines and a potential approach for the cultivation of this underutilised area
Authors(s)	Gillespie, Gary D., McDonnell, Kevin
Publication date	2020-09
Publication information	Gillespie, Gary D., and Kevin McDonnell. "Estimating the Current Area of European Tillage Systems Occupied by Tramlines and a Potential Approach for the Cultivation of This Underutilised Area." Elsevier, September 2020. https://doi.org/10.1016/j.biosystemseng.2020.06.004 .
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/12977
Publisher's version (DOI)	10.1016/j.biosystemseng.2020.06.004

Downloaded 2026-05-01 23:37:21

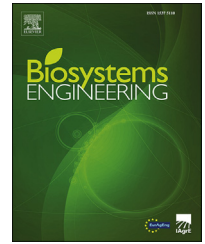
The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Estimating the current area of European tillage systems occupied by tramlines and a potential approach for the cultivation of this underutilised area



Gary D. Gillespie ^{a,c,*}, Kevin P. McDonnell ^{b,c}

^a School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin, 4, Ireland

^b School of Agriculture and Food Science, University College Dublin, Belfield, Dublin, 4, Ireland

^c Biosystems Engineering Ltd., NovaUCD, Belfield, Dublin, 4, Ireland

ARTICLE INFO

Article history:

Received 11 March 2020

Received in revised form

21 May 2020

Accepted 10 June 2020

Keywords:

Tramlines

UAVs

Production

Estimation

Food Security

The global population is growing by 200,000 people per day. In order to provide enough food for this growing populous sustainable intensification methods need to be adopted. The use of technology, and in particular UAVs, may be one of these methods. The use of UAVs for the completion of agricultural tasks such as fertilising and spraying may negate the need for tramlines in European tillage systems. In the present study the amount of land currently occupied by tramlines was determined in an effort to ascertain the potential amount of combinable crop products that could be achieved if this area was utilised. The results of this study found that 3.42% of a field with a 24 m bout width is occupied by tramlines. By using this area for the cultivation of crops an additional 8.14 Mt worth €1.43 billion could be produced. This additional product could provide enough calories to feed 29.5 million people per year.

© 2020 The Author(s). Published by Elsevier Ltd on behalf of IAGrE. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

According to [Kennedy, Bingham, and Spink \(2017\)](#), the global population is increasing by approximately 200,000 people day⁻¹. The [United Nations \(2017\)](#) anticipates that the global population will reach 9.8 billion by the year 2050 and 11.2 billion by the end of the century. This will increase the demand for agricultural production by a predicted 60% by the

year 2050 with the demand for cereals projected to increase from today's 2100 Mt to 3000 Mt ([Kennedy et al., 2017](#); [Khanal, Fulton, & Shearer, 2017](#)). With the growing population, and currently approximately 800 million people undernourished globally ([Boratynska & Huseynov, 2017](#); [Stephens, Jones, & Parsons, 2017](#)), there is an immediate need to improve agricultural systems into highly resource-efficient systems that are both profitable and environmentally sustainable ([Khanal et al., 2017](#)).

* Corresponding author. School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin, 4, Ireland.

E-mail address: gary.gillespie@ucdconnect.ie (G.D. Gillespie).

<https://doi.org/10.1016/j.biosystemseng.2020.06.004>

1537-5110/© 2020 The Author(s). Published by Elsevier Ltd on behalf of IAGrE. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

The main causes of compaction on agricultural land are weight and weight distribution of vehicles (Botta, Tolon Becerra, & Bellora Tourn, 2009; Botta, Tolon Becerra, Lastra-Bravo, & Tourn, 2010; Sivarajan, Maharlooei, Bajwa, & Nowatzki, 2018), and number of passes over a parcel of land (Bakker & Davis, 1995; Hamza & Anderson, 2005; Taghavifar & Mardani, 2014). Results from Kroulik, Kviz, Kumhala, Hula, and Loch (2011) showed that the less the intensity of field operations, the less loading of the soil with machinery passes. As farm machinery gets larger, Gasso, Sorensen, Oudshoorn, and Green (2013) reported that the average mass of tractors in Denmark increased from 2.6 t, in 1970, to 6.6 t, in 2000, and the risk of traffic-induced soil compaction also increases. Keller, Sandin, Colombi, Horn, and Or (2019) and Schjonning et al. (2015) confirm this with Keller et al. (2019) reporting that wheel loads of agricultural tractors have increased from 1.5 Mg in 1960 to 4 Mg in 2000. Increased levels of soil compaction can have a number of negative impacts on cereal production including difficulties in seedbed preparation, seedling emergence, plant growth and root elongation which has an effect on crop development and reduced yields (Bochtis et al., 2010; Rickson et al., 2015). Compacted soil requires deep sub-soiling to alleviate this problem and this would require not only high power tractors but also important investments in fuel and labour time, leading to increased CO₂ emissions (Bochtis et al., 2010; Botta et al., 2009). It is also not a permanent solution to the problem of soil compaction due to the possibility of recompaction. The agricultural worldwide area of detrimental soil compaction was estimated in 1991 to amount to 68 Mha, of which nearly 50% (approximately 33 Mha) was located in Europe, and it is estimated to lead to a potential loss of 20 Mt of grain per annum globally (Gasso et al., 2013; Gasso, Oudshoorn, Sorensen, & Pedersen, 2014; Rickson et al., 2015; Schjonning et al., 2015). Results from Schneider and Don (2019) indicate that 51% of cropland in Germany has been affected by compaction restricting potential rooting to depths of <100 cm.

The conventional approach by tillage farmers in Europe includes the establishment of tramlines during sowing of the crop. Tramlines are narrow, concave, un-vegetated areas that are used as guidance markers for spraying and fertilising operations to prevent under or overlaps during application (Silgram et al., 2015). The adoption of RTK (Real Time Kinematics) has allowed farmers to cultivate tramlines in a field and using guidance travel over the crop for the application of crop inputs. Lowenberg-DeBoer and Erickson (2019) has reported that the uptake of this technology has so far been limited with just 23% of farmers in Denmark having adopted RTK technologies. Also, cultivation of tramlines and travelling over the crop may not be suitable for operations such as later applications of fungicides to treat ear diseases or fertiliser applications for increased protein contents. For this study we have assumed that all tramlines are un-vegetated and thus have no associated crop yield. The bout width (Fig. 1) is the distance from

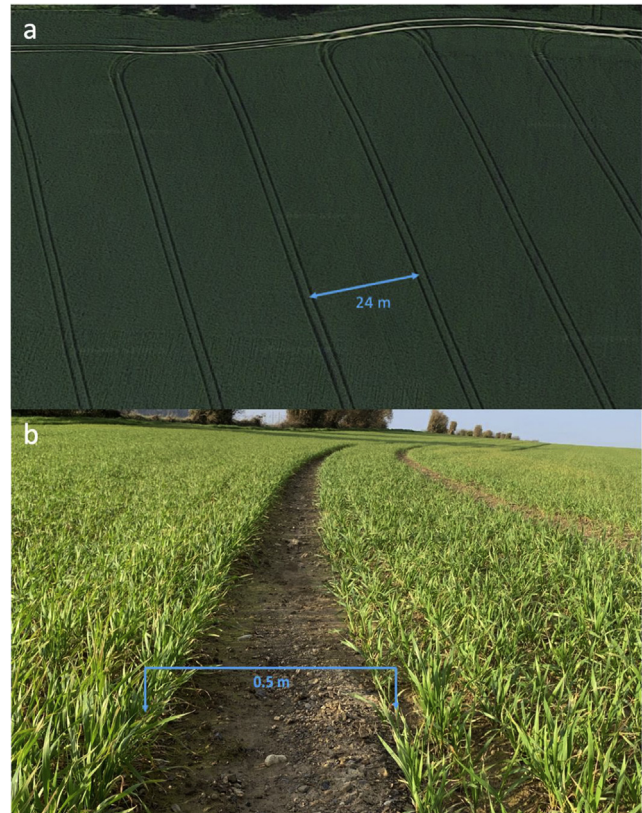


Fig. 1 – a) A high up view of a field in Germany showing parallel tramlines with a bout width of 24m and b) A close up view of a tramline in a wheat field at growth stage 32, showing the uncultivated area that is currently underutilised in tillage production systems.

the centre of one tramline to the centre of an adjacent tramline. These distances can range from 12 to 36 m depending on the width of the machinery used. As outlined by Faical et al. (2017), tramlines are required as field operations are mainly conducted using ground-based machinery which requires permanent contact with the ground during locomotion within the crop field. However, besides allowing machinery access to the interior of the crop, tramlines are also a major transport pathway for surface runoff and associated losses of sediment and phosphorus (Silgram et al., 2015). There is anecdotal evidence of the beneficial effect tramlines can have on the growth of edge rows, however further research is needed to quantify this effect on the growth of edge and adjacent rows.

With recent developments and advances in unmanned aerial vehicles (UAVs), colloquially known as ‘drones’, for agricultural purposes, a number of field operations, such as spraying and fertilising, could be performed from an aerial perspective (Castaldi, Pelosi, Pascucci, & Casa, 2017; Xue, Lan, Sun, Chang, & Hoffmann, 2016; Yang, Yang, & Mo, 2017). Drones are flying robots, which include UAVs that fly thousands of km and small drones that fly in confined spaces

Table 1 – The number of fields from each country that was used in this study.

Country	Bout Width ^a	Area Assessment ^b
Germany	120	12
France	130	10
United Kingdom	90	10
Poland	35	9
Spain	35	2
Sweden	40	1
Italy	20	–
Ireland	20	6
Romania	10	–
Total	500	51

Bold represents the totals of the calculations carried out.

^a The number of fields used to assess the average bout width used in European tillage systems.

^b The number of fields used to calculate the area of a field currently occupied by tramlines.

(Hassanalian & Abdelkefi, 2017). However, the term “drone” is not encouraged as it may evoke an association with hovering robotic predators and government surveillance, so industry promoters prefer the use of Unmanned Aerial Systems (UAS) or UAVs instead (Freeman & Freeland, 2015). By adopting UAVs for more agricultural work, the number of passes over the soil conducted by machinery would reduce, which in turn would decrease the severity of traffic-induced soil compaction on European farms (Hamza & Anderson, 2005; Taghavifar & Mardani, 2014). Utilising UAVs to conduct spraying and fertilizing operations would also negate the need to establish tramlines at the time of sowing.

The aim of this paper is to determine the area of a field that is currently occupied by tramlines and to determine the potential amount of grain that could be produced using this additional land.

2. Materials and methods

2.1. Tramline measurements

The ‘measure distance’ tool in the Google maps software (Google LLC, CA, USA) was used to measure the working width of tramlines in 500 fields across the main cereal growing regions in Europe (Table 1). From this the average bout width (Fig. 1a) of tramlines in Europe was calculated, and was found to be 24 m. Fields that had a bout width of 24 m were then randomly selected ($n = 51$) to calculate the area of tramlines present in a field (Table 1). The field sizes in this study ranged from 1.26 ha to 31.53 ha with an average size of 9.22 ha (standard deviation = 6.88 ha), the total area of the fields involved in this study was 469.97 ha. The width of the tyre tracks (distance from one row of seed to the next, see Fig. 1b) used for the tramlines was found by using a conventional measuring tape on 5 local tillage farms. ten Damme et al. (2019) used tyres for agricultural vehicles that

ranged from 429 to 752 mm in width indicating that the assumption that all tramlines are 0.5 m wide is reasonable on modern arable farms. A crop row spacing of 12.5 cm is generally used throughout Europe (Marshall & Ohm, 1987). The value was adjusted to include the row spacing width of 12.5 cm, which gave a cultivatable area of each tramline of 0.35 m ($0.5 \text{ m} - (2 * 0.125 \text{ m})$), illustrated in Fig. 2, this value was then assumed to be the value used in all cultivated fields across Europe. The length of each tramline wheel track ($\pm 1 \text{ m}$) was found using the ‘measure distance’ tool in Google Maps. These lengths were then multiplied by the cultivatable width of the tyre track (0.35 m, Fig. 2) and summed to give the area of the field used as tramlines. This value was then divided by the total number of hectares in the field to determine the percentage of each field that was utilised for tramlines. As the tramlines in this study were assumed to be un-vegetated, we are assuming that there is no crop yield associated with this area. The equations below show how the area was calculated;

$$\text{Area}_t = \sum l(w)$$

$$\% \text{ Tramlines} = \frac{\text{Area}_t}{(\text{Area}_f * 10,000)} * \frac{100}{1}$$

where, Area_t is the area occupied by tramlines (m^2); Area_f is the area of the field (ha); l is the length of the tramline (m); and w is the cultivatable width of the tyre track (m).

2.2. Agronomic data

The areas (ha) of each of the main combinable broad-acre crops (barley (*Hordeum vulgare*), oats (*Avena sativa*), rapeseed (*Brassica napus*) and wheat (*Triticum aestivum*)) in each European country along with the yield data (t ha^{-1}) for each crop were obtained from statistics published by FAO (2015) for the year 2015. This source was also used to obtain the annual producer prices obtained for each crop, which were converted from $\text{US\$ t}^{-1}$ to € t^{-1} using the average exchange rate for 2015 ($1 \text{ US\$} = \text{€}0.89$).

2.3. Yield adjustment calculations

The yield value reported for each crop includes the areas of the fields that are currently utilised as tramlines. This value was adjusted to represent just the cultivated area of the field and multiplied by the total area of the field to determine the amount of extra product that can be obtained.

The percentage of the field used for tramlines was subtracted from 100% to give a ‘useable area’ factor. This factor was multiplied by the area of each crop ($\text{Area}_{\text{crop}}$) grown to give the actual area that was cultivated (Area_{cul}). The amount of each crop produced was divided by the Area_{cul} to give an adjusted yield value ($\text{Yield}_{\text{adj}}$). The $\text{Yield}_{\text{adj}}$ was then multiplied by the $\text{Area}_{\text{crop}}$ to give the total amount of each crop product possible when tramlines are utilised for crop production. This is expressed mathematically below;

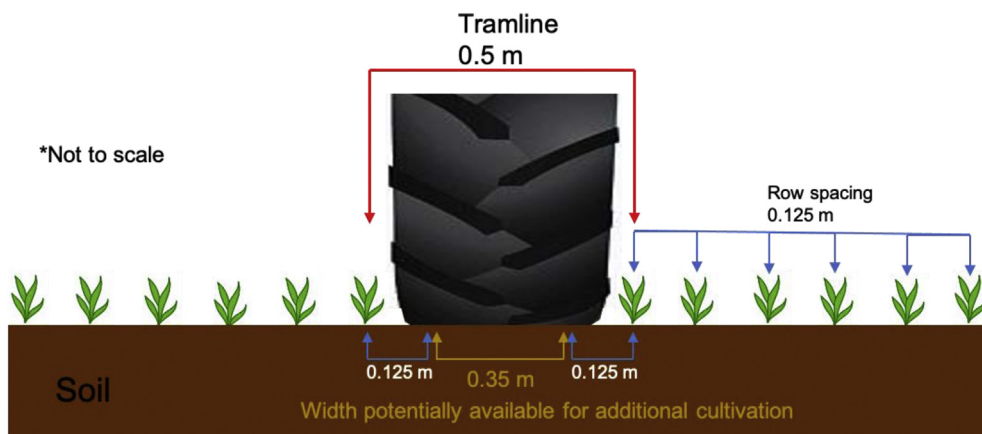


Fig. 2 – Visualisation of the portion of tramlines that is potentially available for further cultivation.

$$\text{Useable area factor} = 1 - \% \text{Area}_t$$

$$\text{Area}_{\text{cul}} = \text{Area}_{\text{crop}} * \text{Useable area factor}$$

$$\text{Yield}_{\text{adj}} = \text{Amount produced} / \text{Area}_{\text{cul}}$$

$$\text{Amount produced}_{\text{adj}} = \text{Yield}_{\text{adj}} * \text{Area}_{\text{crop}}$$

3. Results and discussion

The results of measurements of the 51 tillage fields (Table 1) showed that an average of 3.42% (Min; 2.93%, Max; 4.18%, standard deviation; 0.22%) of a field area is utilised as tramlines. The size and shape of the field had minimal effect on this value, and it appeared to be more affected by the number of obstacles such as trees and utility supports present in a field.

The potential production of each state in the European Union for the four crops analysed in this study were combined and shown in Fig. 3 alongside the potential production of each of the crops in Fig. 4. The current production amounts for each of the four main combinable broad-acre crops are reported in Table 2. This table also reports the amount of each crop that could potentially be produced if tramlines were used for cultivation purposes and the difference between these two values for each of the states in the European Union. From Table 2 it was calculated that by using tramlines for cultivation of crops an additional 8.14 Mt of product could be produced, assuming that all of the required sprays and fertiliser applications for each crop could be applied using UAVs. This is approximately equivalent to the Czech Republic's current output of these four crops. The use of tramlines to cultivate crops would also allow for the current production to be maintained while using less land. The calculations show that current production could be maintained while using 1.67 Mha fewer (an area approximately half the size of Belgium). This would allow for the land to be used for alternative purposes such as solar panels or the cultivation of energy crops or alternative crop management techniques.

3.1. Economic impact

By using the producer price data reported by FAO (2015) for the four crops in each European state, the economic impact of using tramlines for cultivation purposes could be assessed. Table 3 shows the economic value of each crop to each European state. The results show that the total additional crop production, if maximised, would be worth an additional €1.43 billion to European farmers. The authors assume that the addition of the 8.14 Mt of product to the world market will not cause crop prices to reduce due to the growing global population and the resulting increased demand for food.

Also, adoption of UAV technologies by farmers is unlikely to be taken up over a short period of time so the addition of extra product is likely to be over a number of growing seasons thereby limiting the risk of price shocks to markets and farmers.

3.2. Dietary impact

Table 4 shows the average number of calories contained within 100 g of uncooked product, and also the average number of calories that a person requires on a daily basis according to the National Health Service of the U.K. (NHS, 2016). Rapeseed is presented in Table 4 for continuation purposes however the value was not included in calculations as the product is not a major source of dietary calories. By using the production values from Table 2 and calorific values from Table 4, it was calculated that the additional product that would be produced by using tramlines for cultivation would allow for an additional 27 trillion calories to be produced annually. The NHS (2016) recommends 2000 calories day⁻¹ for women and 2500 calories day⁻¹ for men. A value of 2500 calories a day was taken for both, to account for variations such as age, metabolism and physical activity levels. The results indicate (albeit in an over simplified manner) that the additional crop products produced would contain enough calories to feed approximately 29.56 million people a year. This value is roughly equivalent to the combined populations of Australia and New Zealand (United Nations, 2017). With approximately 800 million people undernourished globally (Boratynska & Huseynov, 2017; Godfray et al., 2010; Stephens

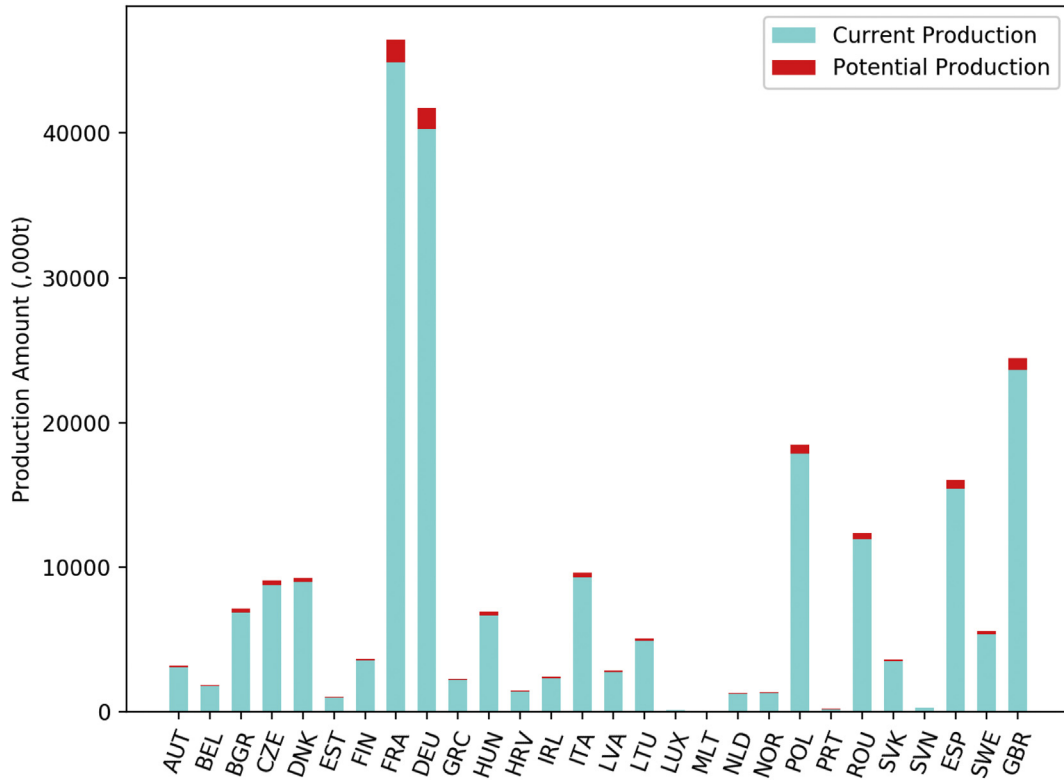


Fig. 3 – Current and potential production amounts for each state in the EU for the four crops utilised in this study.

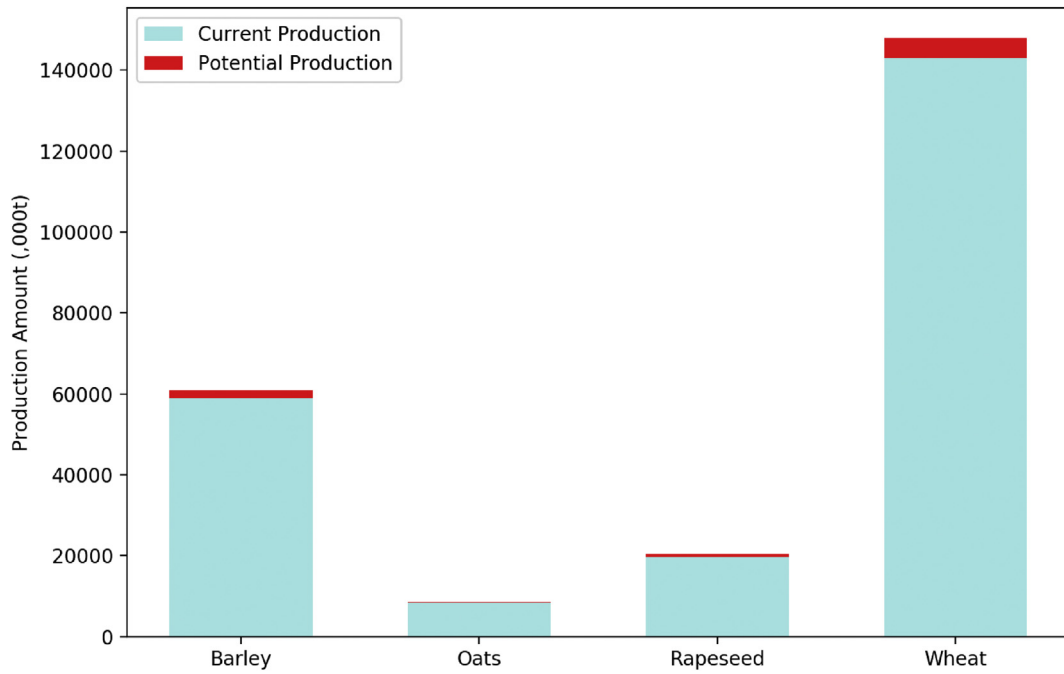


Fig. 4 – Current and potential production amounts for the EU as a whole for each of the crops used in this study.

Table 2 – Recorded and adjusted values of the 4 main broad acre crops studied in this work for each of the European states for 2015.

ISO Code ^a		Barley			Oats			Rapeseed			Wheat		
		Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)
AUT	Rec ^b	140.4	6.12	859.7	22.5	4.21	94.8	39.7	3.58	141.9	315.1	6.25	1970.4
	Adj ^c	135.6	6.34	890.1	21.7	4.36	98.2	38.3	3.70	146.9	304.3	6.47	2040.1
	Diff ^d	-4.8	0.22	30.4	-0.8	0.15	3.4	-1.4	0.13	5.0	-10.8	0.22	69.8
BEL	Rec	55.4	6.24	345.6	3.7	4.47	16.4	11.5	3.44	39.5	206.3	6.79	1400.1
	Adj	53.5	6.46	357.8	3.5	4.63	17.0	11.1	3.57	40.8	199.2	7.03	1449.6
	Diff	-1.9	0.22	12.2	-0.1	0.16	0.6	-0.4	0.12	1.4	-7.1	0.24	49.6
BGR	Rec	159.8	4.32	689.8	15.3	2.05	31.4	171.5	2.97	509.3	1192.6	4.75	5662.8
	Adj	154.4	4.47	714.3	14.8	2.12	32.5	165.6	3.07	527.3	1151.8	4.92	5863.3
	Diff	-5.5	0.15	24.4	-0.5	0.07	1.1	-5.9	0.11	18.0	-40.8	0.17	200.5
CZE	Rec	325.7	5.67	1845.3	37.6	3.52	132.2	393.0	3.46	1359.1	839.7	6.50	5454.7
	Adj	314.6	5.87	1910.6	36.3	3.64	136.9	379.6	3.58	1407.2	811.0	6.73	5647.8
	Diff	-11.1	0.20	65.3	-1.3	0.12	4.7	-13.4	0.12	48.1	-28.7	0.23	193.2
DNK	Rec	706.9	5.59	3949.6	59.5	5.07	301.9	163.2	3.10	506.2	583.0	7.21	4201.5
	Adj	682.7	5.79	4089.5	57.5	5.25	312.6	157.6	3.21	524.1	563.1	7.46	4350.3
	Diff	-24.2	0.20	139.9	-2.0	0.18	10.7	-5.6	0.11	17.9	-19.9	0.26	148.8
EST	Rec	135.3	2.64	357.4	29.3	2.20	64.5	70.1	1.46	102.5	164.5	2.77	455.5
	Adj	130.7	2.73	370.0	28.3	2.28	66.8	67.7	1.51	106.1	158.9	2.87	471.7
	Diff	-4.6	0.09	12.7	-1.0	0.08	2.3	-2.4	0.05	3.6	-5.6	0.10	16.1
FIN	Rec	435.9	3.63	1580.7	305.4	3.40	1037.4	60.4	1.54	92.9	215.1	3.83	823.9
	Adj	421.0	3.75	1636.7	295.0	3.52	1074.1	58.3	1.59	96.2	207.7	3.97	853.1
	Diff	-14.9	0.13	56.0	-10.4	0.12	36.7	-2.1	0.05	3.3	-7.4	0.14	29.2
FRA	Rec	1899.6	5.43	10,306.0	85.5	4.03	344.8	1550.7	3.05	4728.0	5562.6	5.30	29,504.3
	Adj	1834.6	5.62	10,670.9	82.6	4.17	357.1	1497.7	3.16	4895.4	5372.3	5.49	30,549.1
	Diff	-65.0	0.19	364.9	-2.9	0.14	12.2	-53.0	0.11	167.4	-190.2	0.19	1044.8
DEU	Rec	1605.0	6.69	10,730.5	115.5	4.64	535.9	1325.7	3.45	4579.6	3201.7	7.64	24,463.9
	Adj	1550.1	6.92	11,110.5	111.5	4.80	554.9	1280.4	3.58	4741.8	3092.2	7.91	25,330.2
	Diff	-54.9	0.24	380.0	-4.0	0.16	19.0	-45.3	0.12	162.2	-109.5	0.27	866.3
GRC	Rec	154.0	2.64	406.0	47.2	1.70	80.4	7.0	1.91	13.3	612.9	2.77	1698.1
	Adj	148.7	2.73	420.4	45.6	1.76	83.2	6.7	1.98	13.8	591.9	2.87	1758.2
	Diff	-5.3	0.09	14.4	-1.6	0.06	2.8	-0.2	0.07	0.5	-21.0	0.10	60.1
HUN	Rec	271.6	4.26	1157.5	52.9	2.56	135.3	222.1	2.74	608.7	1055.6	4.54	4792.4
	Adj	262.3	4.41	1198.5	51.0	2.65	140.1	214.5	2.84	630.2	1019.5	4.70	4962.1
	Diff	-9.3	0.15	41.0	-1.8	0.09	4.8	-7.6	0.10	21.6	-36.1	0.16	169.7
HRV	Rec	56.5	4.66	263.2	26.6	3.03	80.4	36.8	3.07	113.0	168.0	5.71	960.1
	Adj	54.6	4.82	272.5	25.7	3.13	83.3	35.5	3.18	117.0	162.3	5.92	994.1
	Diff	-1.9	0.16	9.3	-0.9	0.11	2.8	-1.3	0.11	4.0	-5.7	0.20	34.0
IRL	Rec	189.2	7.82	1479.9	23.2	7.90	183.3	9.9	3.44	34.1	67.9	9.54	647.7
	Adj	182.7	8.10	1532.3	22.4	8.18	189.8	9.6	3.57	35.3	65.6	9.88	670.6
	Diff	-6.5	0.28	52.4	-0.8	0.28	6.5	-0.3	0.12	1.2	-2.3	0.34	22.9
ITA	Rec	246.4	4.01	988.3	107.1	2.44	260.8	13.6	2.57	34.9	1912.4	4.20	8037.9
	Adj	237.9	4.15	1023.3	103.4	2.52	270.0	13.1	2.66	36.2	1847.0	4.35	8322.5
	Diff	-8.4	0.14	35.0	-3.7	0.09	9.2	-0.5	0.09	1.2	-65.4	0.15	284.6
LVA	Rec	94.4	3.00	283.2	62.1	2.35	146.1	100.0	2.83	283.0	479.1	4.30	2062.3
	Adj	91.2	3.11	293.2	60.0	2.44	151.3	96.6	2.93	293.0	462.7	4.46	2135.3
	Diff	-3.2	0.11	10.0	-2.1	0.08	5.2	-3.4	0.10	10.0	-16.4	0.15	73.0
LTU	Rec	171.8	3.16	543.1	70.0	2.19	153.2	151.0	2.60	392.5	870.9	4.36	3798.4
	Adj	165.9	3.27	562.3	67.6	2.27	158.7	145.9	2.69	406.4	841.1	4.52	3932.9
	Diff	-5.9	0.11	19.2	-2.4	0.08	5.4	-5.2	0.09	13.9	-29.8	0.15	134.5
LUX	Rec	6.9	4.93	34.0	1.1	4.83	5.3	3.5	3.11	10.9	13.8	5.07	70.1
	Adj	6.7	5.10	35.2	1.1	5.01	5.5	3.4	3.22	11.3	13.3	5.25	72.5
	Diff	-0.2	0.17	1.2	0.0	0.17	0.2	-0.1	0.11	0.4	-0.5	0.18	2.5
MLT	Rec	0.5	4.15	2.1	0.0	0	0.0	0.0	0	0.0	3.3	4.84	16.0
	Adj	0.5	4.30	2.2	0.0	0	0.0	0.0	0	0.0	3.2	5.01	16.5
	Diff	0.0	0.15	0.1	0.0	0	0.0	0.0	0	0.0	-0.1	0.17	0.6
NLD	Rec	34.4	6.86	236.2	1.5	4.80	7.1	1.6	3.30	5.3	127.3	7.98	1016.5
	Adj	33.3	7.10	244.6	1.4	4.97	7.3	1.5	3.42	5.5	123.0	8.27	1052.5
	Diff	-1.2	0.24	8.4	-0.1	0.17	0.3	-0.1	0.12	0.2	-4.4	0.28	36.0
NOR	Rec	137.2	4.57	626.9	76.0	4.66	354.3	4.1	2.75	11.4	66.8	4.62	308.8
	Adj	132.5	4.73	649.1	73.4	4.83	366.8	4.0	2.85	11.8	64.5	4.79	319.7
	Diff	-4.7	0.16	22.2	-2.6	0.17	12.5	-0.1	0.10	0.4	-2.3	0.16	10.9

Table 2 – (continued)

ISO Code ^a		Barley			Oats			Rapeseed			Wheat		
		Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)	Area ('000 Ha)	Yield (t ha ⁻¹)	Amount ('000 t)
POL	Rec	926.1	3.72	3441.1	477.9	2.84	1358.1	826.9	2.68	2219.3	2384.1	4.54	10,827.9
	Adj	894.5	3.85	3563.0	461.5	2.94	1406.2	798.7	2.78	2297.9	2302.5	4.70	11,211.3
	Diff	-31.7	0.13	121.9	-16.3	0.10	48.1	-28.3	0.10	78.6	-81.5	0.16	383.4
PRT	Rec	20.6	2.26	46.6	42.4	1.55	65.8	0.0	0	0.0	38.2	2.36	90.0
	Adj	19.9	2.34	48.3	41.0	1.61	68.1	0.0	0	0.0	36.9	2.44	93.2
	Diff	-0.7	0.08	1.7	-1.5	0.05	2.3	0.0	0	0.0	-1.3	0.08	3.2
ROU	Rec	480.9	3.78	1817.3	169.6	2.25	381.4	455.0	2.84	1292.8	2135.3	3.95	8431.0
	Adj	464.5	3.91	1881.6	163.8	2.33	394.9	439.5	2.94	1338.6	2062.3	4.09	8729.6
	Diff	-16.4	0.13	64.4	-5.8	0.08	13.5	-15.6	0.10	45.8	-73.0	0.14	298.6
SVK	Rec	115.0	5.08	584.6	13.6	2.62	35.6	124.5	3.46	430.5	416.6	5.84	2434.2
	Adj	111.0	5.26	605.3	13.1	2.71	36.9	120.2	3.58	445.8	402.3	6.05	2520.4
	Diff	-3.9	0.18	20.7	-0.5	0.09	1.3	-4.3	0.12	15.2	-14.2	0.21	86.2
SVN	Rec	19.2	4.78	91.7	1.3	3.24	4.3	3.2	2.72	8.6	31.5	5.19	163.2
	Adj	18.5	4.95	94.9	1.3	3.36	4.5	3.0	2.82	8.9	30.4	5.37	168.9
	Diff	-0.7	0.17	3.2	0.0	0.11	0.2	-0.1	0.10	0.3	-1.1	0.18	5.8
ESP	Rec	2800.6	2.85	7979.5	468.3	1.89	884.8	75.5	2.04	154.3	2078.1	3.10	6433.8
	Adj	2704.8	2.95	8262.1	452.3	1.96	916.1	72.9	2.12	159.8	2007.0	3.21	6661.7
	Diff	-95.8	0.10	282.6	-16.0	0.07	31.3	-2.6	0.07	5.5	-71.1	0.11	227.8
SWE	Rec	318.6	4.80	1530.4	172.9	4.44	767.9	92.7	2.89	268.1	448.5	6.32	2834.5
	Adj	307.7	4.97	1584.6	167.0	4.60	795.1	89.5	2.99	277.6	433.1	6.54	2934.9
	Diff	-10.9	0.17	54.2	-5.9	0.16	27.2	-3.2	0.10	9.5	-15.3	0.22	100.4
GBR	Rec	1122.0	5.93	6655.0	141.0	5.79	816.0	579.0	3.07	1775.0	1823.0	7.89	14,382.9
	Adj	1083.6	6.14	6890.7	136.2	5.99	844.9	559.2	3.17	1837.8	1760.7	8.17	14,892.2
	Diff	-38.4	0.21	235.7	-4.8	0.20	28.9	-19.8	0.11	62.9	-62.3	0.28	509.3
Total	Rec	12,630.0	130	58,831.2	2628.8	95	8279.3	6492.2	74	19,714.6	27,013.8	148	142,942.8
	Adj	12,198.1	134	60,914.5	2538.9	98	8572.5	6270.2	77	20,412.7	26,089.9	153	148,004.6
	Diff	-431.9	4.59	2083.3	-89.9	3.35	293.2	-222.0	2.62	698.1	-923.9	5.25	5061.8

^a Countries are arranged based on the 3 digit ISO Alpha-3 code.

^b Actual data reported by the FAO.

^c Values adjusted using equations outlined in this work.

^d The difference between the adjusted and reported values.

et al., 2017) this additional material would help to substantially increase food security on a global level.

3.3. Agronomic discussion

This study has demonstrated that over 3% of a field is occupied by tramlines, which are used primarily for vehicular access to the centre of a field. Using UAVs for agricultural tasks such as spraying pesticides and applying fertiliser would allow this area to be used either for additional cultivation of crops, the establishment of energy crops or solar panels or for ecological areas to aid with pest control. Using UAVs instead of conventional agricultural tractors to complete the spraying and fertilising tasks would allow the area currently used as tramlines to be established as permanent wildflower strips in fields to encourage both crop pollinators and predators of pests without affecting the area cultivated by farmers. Further research into the effect of wildflower strips on crop yields and economic returns will determine how effective this technique may be for farmers. Increasing cultivated cropping areas by opening new parcels of arable land from alternative uses such as forestry must be curtailed as far as possible because of the huge environmental costs, including biodiversity loss and greenhouse gas emissions associated with the land use change (Fischer & Connor, 2018). Therefore, sustainable

methods for intensification of cereal production need to be considered, such as removing tramlines from fields and using this area for cultivation of crops.

Numerous studies (Deasy et al., 2009; Silgram et al., 2015; Silgram, Jackson, Bailey, Quinton, & Stevens, 2010; Withers, Hodgkinson, Bates, & Withers, 2006) have found that the losses of sediment and phosphorus (P) from tramlines are significantly higher than from areas without tramlines. The findings of these studies concur with the results of an earlier survey of 146 arable fields conducted by Chambers, Garwood, and Unwin (2000), who found that tramlines were a major causal factor in 34% of fields where erosion occurred. Silgram et al. (2010) found losses of P on both sandy loam and silty-clay loam soils with a slope of 4° in England were 0.8–2.9 kg [total P] ha⁻¹ for areas with tramlines compared with losses of 0.0–0.2 kg [total P] ha⁻¹ for areas without tramlines. Withers et al. (2006) reported that plots with tramlines on a fine sandy soil with a slope of 5° had on average 46% more runoff than plots without tramlines. This resulted in an increase of 0.3 kg [total P] ha⁻¹ and 0.4 t of sediment ha⁻¹ being lost from the plots. The removal of tramlines, particularly from areas that are prone to runoff, could have a substantial impact on the amount of sediment and P entering aquatic systems while increasing the efficiency of arable crop production.

Table 3 – The economic return from the current and potential production of each of the crops used for the EU member states.

ISO Code	Crop ^b	€ t ⁻¹	Amount ('000 t) ^a	Value ('000 €)	ISO Code	Crop	€ t ⁻¹	Amount ('000 t)	Value ('000 €)
AUT	Bar	117	30.44	3547	LAT	Bar	131	10.0	1316
	Oat	112	3.36	374		Oat	113	5.2	587
	Rap	331	5.02	1661		Rap	331	10.0	3313
	Whe	135	69.77	9433		Whe	146	73.0	10,666
BEL	Bar	141	12.24	1720	LTU	Bar	142	19.2	2725
	Oat	66	0.58	38		Oat	120	5.4	649
	Rap	224	1.40	313		Rap	337	13.9	4680
BGR	Whe	152	49.58	7559	LUX	Whe	160	134.5	21,536
	Bar	153	24.43	3735		Bar	140	1.2	169
	Oat	182	1.11	202		Oat	116	0.2	22
HRV	Rap	338	18.03	6099	MLT	Rap	337	0.4	130
	Whe	154	200.52	30,839		Whe	154	2.5	382
	Bar	155	9.32	1448		Bar	825	0.1	62
	Oat	138	2.85	394		Oat	743	0.6	421
CZE	Rap	341	4.00	1366	NLD	Rap		0	0
	Whe	150	34.00	5117		Whe		0	0
	Bar	160	65.34	10,433		Bar	157	8.4	1315
	Oat	161	4.68	752		Oat	143	0.3	36
DNK	Rap	357	48.13	17,168	NOR	Rap	320	0.2	60
	Whe	149	193.16	28,863		Whe	157	36.0	5648
	Bar	159	139.86	22,293		Bar	286	22.2	6360
	Oat	141	10.69	1506		Oat	258	12.5	3236
EST	Rap	344	17.92	6163	POL	Rap	565	0.4	228
	Whe	153	148.78	22,749		Whe	309	10.9	3382
	Bar	140	12.66	1774		Bar	145	121.9	17,612
	Oat	130	2.28	296		Oat	116	48.1	5577
FIN	Rap	372	3.63	1352	PRT	Rap	355	78.6	27,928
	Whe	145	16.13	2332		Whe	158	383.4	60,572
	Bar	134	55.97	7512		Bar	193	1.7	319
	Oat	133	36.74	4894		Oat	179	2.3	416
FRA	Rap	353	3.29	1162	ROU	Rap	209	3.2	666
	Whe	167	29.18	4866		Whe		0	0
	Bar	148	364.95	54,079		Bar	191	64.4	12,297
	Oat	144	12.21	1756		Oat	202	13.5	2731
DEU	Rap	353	167.42	59,156	SLK	Rap	364	45.8	16,680
	Whe	155	1044.78	161,981		Whe	164	298.6	49,077
	Bar	143	379.98	54,380		Bar	158	20.7	3279
	Oat	147	18.98	2792		Oat	235	1.3	296
GRC	Rap	345	162.17	56,029	SLN	Rap	355	15.2	5410
	Whe	160	866.29	138,549		Whe	151	86.2	12,996
	Bar	165	14.38	2373		Bar	132	3.2	429
	Oat	166	2.85	473		Oat	168	0.2	26
HUN	Rap	364	0.47	171	ESP	Rap	359	0.3	109
	Whe	228	60.13	13,737		Whe	166	5.8	960
	Bar	134	40.99	5472		Bar	172	282.6	48,536
	Oat	136	4.79	652		Oat	180	31.3	5633
IRE	Rap	360	21.55	7764	SWE	Rap	315	5.5	1723
	Whe	155	169.70	26,310		Whe	200	227.8	45,521
	Bar	114	52.40	5993		Bar	131	54.2	7076
	Oat	107	6.49	691		Oat	115	27.2	3139
ITA	Rap	850	1.21	1026	GBR	Rap	333	9.5	3159
	Whe	113	22.94	2582		Whe	149	100.4	14,954
	Bar	136	35.00	4769		Bar	143	235.7	33,642
	Oat	221	9.24	2044		Oat	147	28.9	4243
	Rap	223	1.24	276		Rap	343	62.9	21,537
	Whe	192	284.63	54,692		Whe	169	509.3	85,853
Total								8136	1,425,028

Bold represents the totals of the calculations carried out.

^a cf. Table 2.

^b Bar; Barley, Rap; Rapeseed, Whe; Wheat.

Table 4 – Average calories contained in each of the broad-acre crops used in this study.

Crop	Calories t ^{-1a}
Barley	3,520,000
Oats	3,890,000
Rapeseed	3,980,000
Wheat	3,270,000
Calorific Intake ^b	913,125

^a Values from USDA database.
^b Reference calorific requirements (2500 calories day⁻¹) according to the NHS.

In recent years there has been a growing demand for controlled release or polymer coated fertilisers (Shaviv, 2000). These fertilisers are granulated fertilisers that are coated with compounds that allow for the gradual release of the nutrients, the rate of which is dependent on the solubility of the compound in the soil moisture (Ahmad, Fernando, & Uzir, 2015; Liu, Yang, Gao, Li, & Xie, 2019; Shaviv, 2000). Further advances in these products that account for total nutrient requirement, specific periods of peak nutrient demand, and preferred chemical forms which are specific to each crop and variety, may allow for all of a crop's fertiliser requirements to be applied to the seed bed (Macholdt, Piepho, & Honermeier, 2019; Shaviv, 2000). The application of all fertiliser requirements during seed bed preparation would then allow for UAVs to be used solely for the application of plant protection products.

The establishment and harvest of each crop would still be conducted using existing equipment and the UAVs would only be required for conducting spraying and fertilising operations. As the cultivation equipment and sowing equipment is used on the entire field during the field operations, there are no additional operational costs to be included if the tramlines are to be sown. There is a marginal increase in the cost of additional seed necessary for the sowing of these tramlines. However, as growers tend to purchase seed on a "whole" field basis rather than an actual sown area basis – this cost is minimal.

3.4. Current capabilities of UAVs

The current market leader for UAV production is DJI (Shenzhen DJI-Innovations Technology Co., Ltd., Shenzhen, China) with a >70% market share for non-recreational UAVs (Gettinger & Holland Michel, 2017). Due to current legislation in the EU surrounding the operation of non-recreational UAVs, prices for agricultural UAVs are not readily available. However, in China, DJI has released 2 UAV models that are capable of applying plant protection products, the T16 model and the MG-1P model. These UAVs have a retail price, in China, of €4250 and €6,130, respectively. These prices are for the UAVs and exclude accessories such as controllers, extra batteries and insurance, etc. The T16 model has 8 spray nozzles and a tank capable of storing 16 L of product, and is equipped with a 17,500 mAh battery, which gives it a flight time when fully loaded of approximately 10 min. The MG-1P has a 10 L tanks with 4 spray nozzles and is equipped with a

12,000 mAh battery. The company claims that the T16 can spray up to 10 ha h⁻¹. The controller for these UAVs is also capable of controlling up to 5 machines at one time allowing for one operator to spray a theoretical maximum of 50 ha h⁻¹. It is unlikely to reach this figure due to the time that would be required for refilling of plant protection products, battery changes and routine in-field maintenance. Xiongkui, Bonds, Herbst, and Langenakens (2017) reported that UAVs operating in China with a spray tank capacity of 5–20 L and a bout width of 5–20 m had operating efficiencies of 6–10 ha h⁻¹. Hunter, Gannon, Richardson, Yelverton, and Leon (2020) found that a UAV system was 4% more precise and had a higher application efficiency (87% for the UAV compared to 68% for the ground-based system) when applying herbicide to treat the weed *Kummerowia striata* in two fields in the USA.

Nordmeyer (2009) studied the spatial and temporal dynamics of an important grass weed in winter cereals (*Apera spica-venti*) between 1999 and 2006 and found that the auto-correlation of the majority of the weeds spans short distances, i.e. the ranges of the semi-variogram are generally small, in the order of 30–50 m (Castaldi et al., 2017). This means that blanket applications for the control of weeds may be unnecessary, depending on the severity of the weed infestation. Castaldi et al. (2017) used a prescription herbicide map to apply herbicides to 4 fields of maize and used between 14 and 39% less of post emergence herbicide depending on the field. The use of UAVs with imaging technologies that are capable of identifying regions of a field where pest and disease pressures are high could reduce the amount of plant protection products needed (Castaldi et al., 2017; Faical et al., 2017; Rodriguez-Moreno et al., 2016). This would then allow for the limited flight time of UAVs to cover a greater proportion of an affected field, by only applying plant protection products to areas that are in need of them. It would also reduce the overall use of plant protection products in Europe, which would be a benefit from an environmental and biodiversity standpoint (Aktar, Sengupta, & Chowdhury, 2009; Deknock et al., 2019; Sponsler et al., 2019). Wang et al. (2019) compared a UAV sprayer with a 6m boom sprayer and found that the UAV had a working efficiency of 4.11 ha h⁻¹ compared with 2.38 ha h⁻¹ for the boom sprayer. There has been very limited work comparing the use of UAV sprayers with boom sprayers and the authors could find no similar study that used a large boom sprayer (24 m) that is commonly used in European tillage systems. Future studies should compare the working efficiency of UAVs with large equipment used in European tillage systems over both whole field situations and spatial regions of a field affected by pests and diseases.

As UAVs are airborne vehicles, they may be more susceptible to adverse weather conditions limiting the number of days that they can operate in and possibly increasing the risk of drift of plant protection products. Zhu, Li, Zhang, Li, and Zhang (2019) developed computational fluid dynamic models to determine the effect of wind speed, spray height and nozzle pressures on the droplet deposition distribution from UAV systems. These models can help to ensure that future chemical applications minimise the drift of plant protection products and maximise efficacy. Faical et al. (2017) developed a system that accounts for changing weather conditions; mainly wind speed and direction, to adjust the flight route of

the UAV to ensure that any chemicals applied remain within the target area. With these technological advances applied to UAV systems, the drift from plant protection products should be minimised and allow for the application of chemical products in weather conditions that were previously unsuitable.

The authors acknowledge that this paper does make a number of assumptions in their calculations; however, the results demonstrate the potential cropping area and yield that are currently underutilised in European tillage systems. Further research into the effect of tramlines on the yield and quality of crops due to tramlines is needed. The effect of using vegetated tramlines and travelling over crops on yield also needs to be assessed before the adoption of UAV systems can be fully implemented onto arable farms.

4. Conclusions

With the global population growing by 200,000 people day⁻¹ and changing dietary patterns, the demand for food will substantially increase over the coming decades. In combination with the use of controlled-release polymer-coated fertilisers that would be applied prior to sowing, the developments in UAV technologies would enable these tools to be used to complete the common agricultural tasks of pesticide and fungicide applications and would negate the need for tramlines in tillage fields. This study has found that on average 3.42% of tillage fields are occupied by tramlines. In Europe the total area of land occupied by tramlines equates to 1.67 Mha. By using these tramlines for the cultivation of crops an additional 8.14 Mt worth €1.43 billion could be produced. This additional material contains enough calories to feed 29.56 million people annually. This study demonstrates that using UAVs in agriculture can lead to substantial increases in food security and lead to a greater economic return for farmers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful for the inputs from Dr. Paul Brooks for the checking of language and layout modifications. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

Ahmad, N., Fernando, W., & Uzir, M. (2015). Parametric evaluation using mechanistic model for release rate of phosphate ions from chitosan-coated phosphorus fertiliser pellets. *Biosystems Engineering*, 129, 78–86.

- Aktar, M., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology*, 2(1), 1–12.
- Bakker, D., & Davis, R. (1995). Soil deformation observations in a vertisol under field traffic. *Australian Journal of Soil Research*, 33(5), 817–832.
- Bochtis, D., Sorensen, C., Busato, P., Hameed, I., Rodias, E., Green, O., & Papadakis, G. (2010). Tramline establishment in controlled traffic farming based on operational machinery cost. *Biosystems Engineering*, 107, 221–231.
- Boratynska, K., & Huseynov, R. (2017). An innovative approach to food security policy in developing countries. *Journal of Innovation and Knowledge*, 2, 39–44.
- Botta, G., Tolon Becerra, A., & Bellora Tourn, F. (2009). Effect of the number of tractor passes on soil rut depth and compaction in two tillage regimes. *Soil and Tillage Research*, 103, 381–386.
- Botta, G., Tolon Becerra, A., Lastra-Bravo, X., & Tourn, M. (2010). Tillage and traffic effects (planters and tractors) on soil compaction and soybean (*Glycine max* L.) yields in Argentinean pampas. *Soil and Tillage Research*, 110, 167–174.
- Castaldi, F., Pelosi, F., Pascucci, S., & Casa, R. (2017). Assessing the potential of images from unmanned aerial vehicles (UAV) to support herbicide patch spraying in maize. *Precision Agriculture*, 18(1), 76–94.
- Chambers, B., Garwood, T., & Unwin, R. (2000). Controlling soil water erosion and phosphorus losses from arable land in England and Wales. *Journal of Environmental Quality*, 29, 145–150.
- Deasy, C., Quinton, J., Silgram, M., Bailey, A., Jackson, B., & Stevens, C. (2009). Mitigation options for sediment and phosphorus loss from winter-sown arable crops. *Journal of Environmental Quality*, 38, 2121–2130.
- Deknock, A., De Troyer, N., Houbraken, M., Dominguez-Granda, L., Noliivos, I., Van Echelpoel, W., ... Goethals, P. (2019). Distribution of agricultural pesticides in the freshwater environment of the Guayas river basin (Ecuador). *The Science of the Total Environment*, 646, 996–1008.
- Faical, B., Freitas, H., Gomes, P., Mano, L., Pessin, G., de Carvalho, A., ... Ueyama, J. (2017). An adaptive approach for UAV-based pesticide spraying in dynamic environments. *Computers and Electronics in Agriculture*, 138, 210–223.
- FAO. (2015). FAOstat, 2015.
- Fischer, R., & Connor, D. (2018). Issues for cropping and agricultural science in the next 20 years. *Field Crops Research*, 222, 121–142.
- Freeman, P., & Freeland, R. (2015). Agricultural UAVs in the U.S.: Potential, policy, and hype. *Remote Sensing Applications: Society and Environment*, 2, 35–43.
- Gasso, V., Oudshoorn, F., Sorensen, C., & Pedersen, H. (2014). An environmental life cycle assessment of controlled traffic farming. *Journal of Cleaner Production*, 73, 175–182.
- Gasso, V., Sorensen, C., Oudshoorn, F., & Green, O. (2013). Controlled traffic farming: A review of the environmental impacts. *European Journal of Agronomy*, 48, 66–73.
- Gettinger, D., & Holland Michel, A. (2017). Drone registrations; A preliminary analysis. In B. College (Ed.). Retrieved from <http://dronecenter.bard.edu/drone-registrations/>. (Accessed 23 September 2019).
- Godfray, C., Beddington, J., Crute, I., Haddad, L., Lawrence, D., Muir, J., ... Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, 327, 812–818.
- Hamza, M., & Anderson, W. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82, 121–145.
- Hassanalian, M., & Abdelkefi, A. (2017). Classifications, applications, and design challenges of drones: A review. *Progress in Aerospace Sciences*, 91, 99–131.

- Hunter, J., Gannon, T., Richardson, R., Yelverton, F., & Leon, R. (2020). Integration of remote-weed mapping and an autonomous spraying unmanned aerial vehicle for site-specific weed management. *Pest Management Science*, 76(4), 1386–1392. <https://doi.org/10.1002/ps.5651>.
- Keller, T., Sandin, M., Colombi, T., Horn, R., & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*, 194, 104293. <https://doi.org/10.1016/j.still.2019.104293>.
- Kennedy, S., Bingham, I., & Spink, J. (2017). Determinants of spring barley yield in a high-yield potential environment. *Journal of Agricultural Science*, 155, 60–80.
- Khanal, S., Fulton, J., & Shearer, S. (2017). An overview of current and potential applications of thermal remote sensing in precision agriculture. *Computers and Electronics in Agriculture*, 139, 22–32.
- Kroulik, M., Kviz, Z., Kumbhala, F., Hula, J., & Loch, T. (2011). Procedures of soil farming allowing reduction of compaction. *Precision Agriculture*, 12, 317–333.
- Liu, J., Yang, Y., Gao, B., Li, Y., & Xie, J. (2019). Bio-based elastic polyurethane for controlled-release urea fertilizer: Fabrication, properties, swelling and nitrogen release characteristics. *Journal of Cleaner Production*, 209, 528–537.
- Lowenberg-DeBoer, J., & Erickson, B. (2019). Setting the record straight on precision agriculture adoption. *Agronomy Journal*, 111(4), 1552–1569. <https://doi.org/10.2134/agronj2018.12.0779>.
- Macholdt, J., Piepho, H., & Honermeier, B. (2019). Mineral NPK and manure fertilisation affecting the yield stability of winter wheat: Results from a long-term field experiment. *European Journal of Agronomy*, 102, 14–22.
- Marshall, G. C., & Ohm, H. (1987). Yield responses of 16 winter wheat cultivars to row spacing and seeding rate. *Agronomy Journal*, 79(6), 1027–1030.
- NHS. (2016). *What should my daily intake of calories be?*. Retrieved February, 2018, from <https://www.nhs.uk/chaq/pages/1126.aspx?categoryid=51>.
- Nordmeyer, H. (2009). Spatial and temporal dynamics of *Apera spica-venti* seedling populations. *Crop Protection*, 28, 831–837.
- Rickson, R., Deeks, L., Graves, A., Harris, J., Kibblewhite, M., & Sakrabani, R. (2015). Input constraints to food production: The impact of soil degradation. *Food Security*, 7, 351–364.
- Rodriguez-Moreno, F., Zemek, F., Kren, J., Píkl, M., Lukas, V., & Novak, J. (2016). Spectral monitoring of wheat canopy under uncontrolled conditions for decision making purposes. *Computers and Electronics in Agriculture*, 125, 81–88.
- Schjonning, P., van den Akker, J., Keller, T., Greve, M., Lamandé, M., Simojoki, A., ... Breuning-Madsen, H. (2015). Chapter 5 - driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction - a European perspective. *Advances in Agronomy*, 133, 183–237.
- Schneider, F., & Don, A. (2019). Root-restricting layers in German agricultural soils. Part I: Extent and cause. *Plant and Soil*, 442, 433–451.
- Shaviv, A. (2000). Advance in controlled release fertilizers. *Advances in Agronomy*, 71, 1–49.
- Silgram, M., Jackson, D., Bailey, A., Quinton, J., & Stevens, C. (2010). Hillslope scale surface runoff, sediment and nutrient losses associated with tramline wheelings. *Earth Surface Processes and Landforms*, 35, 699–706.
- Silgram, M., Jackson, B., McKenzie, B., Quinton, J., Williams, D., Harris, D., ... Zhang, Y. (2015). Reducing the risks associated with autumn wheeling of combinable crops to mitigate runoff and diffuse pollution: A field and catchment scale evaluation. In A. C. Oilseeds (Ed.), *Project report No. 559*. United Kingdom.
- Sivarajan, S., Maharlooei, M., Bajwa, S., & Nowatzki, J. (2018). Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. *Soil and Tillage Research*, 175, 234–243.
- Sponsler, D., Grozinger, C., Hitaj, C., Rundlof, M., Botias, C., Code, A., ... Douglas, M. (2019). Pesticides and pollinators: A socioecological synthesis. *The Science of the Total Environment*, 662, 1012–1027.
- Stephens, E., Jones, A., & Parsons, D. (2017). Agricultural systems research and global food security in the 21st century: An overview and roadmap for future opportunities. *Agricultural Systems*. In Press, Corrected Proof.
- Taghavifar, H., & Mardani, A. (2014). Effect of velocity, wheel load and multipass on soil compaction. *Journal of the Saudi Society of Agricultural Sciences*, 13, 57–66.
- ten Damme, L., Stettler, M., Pinet, F., Vervae, P., Keller, T., Munkholm, L. J., & Lamandé, M. (2019). The contribution of tyre evolution to the reduction of soil compaction risks. *Soil and Tillage Research*, 194, 104283. <https://doi.org/10.1016/j.still.2019.05.029>.
- United Nations. (2017). *World population prospects: The 2017 revision, data booklet*. Department of Economic and Social Affairs, Population Division.
- Wang, L., Lan, Y., Zhang, Y., Zhang, H., Naveed Tahir, M., Ou, S., ... Chen, P. (2019). Applications and prospects of agricultural unmanned aerial vehicle obstacle avoidance technology in China. *Sensors*, 19, 642–658.
- Withers, P., Hodgkinson, R., Bates, A., & Withers, C. (2006). Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. *Soil Use & Management*, 22, 245–255.
- Xiongfui, H., Bonds, J., Herbst, A., & Langenakens, J. (2017). Recent development of unmanned aerial vehicle for plant protection in East Asia. *International Journal of Agricultural and Biological Engineering*, 10(3), 18–30. <https://doi.org/10.3965/ij.ijabe.20171003.3248>.
- Xue, X., Lan, Y., Sun, Z., Chang, C., & Hoffmann, C. (2016). Develop an unmanned aerial vehicle based automatic aerial spraying system. *Computers and Electronics in Agriculture*, 128, 58–66.
- Yang, S., Yang, X., & Mo, J. (2017). The application of unmanned aircraft systems to plant protection in China. *Precision Agriculture*, 1–15.
- Zhu, H., Li, H., Zhang, C., Li, J., & Zhang, H. (2019). Performance characterization of the UAV chemical application based on CFD simulation. *Agronomy*, 9, 308.