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Controlled traffic farming and field traffic management: Perceptions of farmers groups from Northern and Western European countries

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ABSTRACT

As farming machinery size and weight increases, soil compaction continues to threaten mechanized agriculture. Controlled Traffic Farming (CTF) minimizes soil compaction in the crop zone by restricting traffic to permanent tracks. The adoption of CTF in Europe is low. This study enhances the understanding of farmers' needs and perceptions concerning the application of CTF by analyzing survey data from 103 farmers sampled from 8 European countries. The study adopted a descriptive approach to data analysis. Awareness about traffic-induced soil compaction is high among surveyed farmers and there are positive perceptions about the potential of CTF. The major factors limiting adoption of CTF appear to be: lack of compatibility in machinery and Global Navigation Satellite Systems (GNSS) by different manufacturers; expense (equipment purchase, Real-time Kinematic (RTK) signal, machinery modification); lack of demonstrated benefits under local conditions; incomplete knowledge of research findings and decision support tools; and a perception that CTF is not for small farms. The following interventions are suggested for future development and use of CTF: a shift towards lighter, simpler, adaptable, and energy effective machinery; adapted market models for cost-effective provision of basic services; demonstration of costs and benefits under local conditions in tandem with demand-driven decision support tools as well as standardization of equipment and positioning systems.

1. Introduction

As farm machinery grows bigger and heavier in pursuit of economies of scale, traffic-induced soil compaction has become widespread. ESDAC (2008) defined soil compaction as ". a form of physical degradation resulting in densification and distortion of the soil where biological activity, porosity and permeability are reduced, strength is increased, and soil structure is partly destroyed". Manifestations of soil compaction are multifaceted (Beylich et al., 2010; Raper, 2005). Soil compaction causes a loss of nitrogen from soil (Gregorich et al., 2014; Ruser et al., 2006) resulting in a reduction of soil nitrogen uptake by plants (Gregorich et al., 2014; Ruser et al., 1998). Yamulki and Jarvis (2002) found that compaction had a more profound effect than tillage on the release of gaseous emissions from agriculture. Tullberg et al. 2018) found evidence that trafficked soils have significantly higher N_2O emissions than non-trafficked soils (by an average factor of 2.2). Pangnakorn et al. (2003) documented significant difference in earthworm populations between compacted and non-compacted soils.

Subsoil compaction can persist over a long time (Alaoui and Diserens, 2018) and is costly to eliminate, if elimination is possible at all (ESDAC, 2008). Hence, there is a need for smart agricultural techniques to avoid compaction (Govers et al., 2017). Managing machinery traffic in terms of: the placement of machinery traffic pathways; the axle loads, tyre sizes and inflation pressures used; and the soil conditions under which trafficking is allowed, can contribute to compaction avoidance. One such approach is to confine field traffic to permanent tracks that are

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maintained year after year, referred to as Controlled Traffic Farming (CTF) (McPhee and Aird, 2013; Tullberg et al., McGarry, 2007).

Earlier deployment of CTF technology relied on marking permanent tracks and frequently involved the deployment of gantries. The advent of high precision positioning and auto-steering systems, by avoiding the need to physically mark and manually steer along pathways, makes CTF a promising technology in future agriculture (Gasso et al., 2013, 2014). In Chamen (2008), CTF is labeled as "precision farming at its most efficient". In its strict sense, CTF requires all machinery operations to be in permanent tracks. Today, unlike the original gantry systems where one set of uncropped pathways received the same amount of traffic, a CTF managed field may have different pathways, some cropped and some uncropped, receiving different levels of traffic depending on the implement working widths, but all in multiples of the narrowest machine working width. CTF can also be viewed and implemented differently in different regions and/or across different farming groups with 'seasonal CTF' for example deploying a CTF system after primary cultivation until the end of that season or until the harvesting operation.

The essence of CTF is to eliminate soil compaction within the cropped area, improve tractive efficiency on the permanent tracks, and thereby improve crop yield and economic return. Setting a CTF system on a farm is often made over years during which the machines being replaced are chosen, or they are modified, to match the CTF system chosen. Mainly a base working width has to be chosen (in Europe, often 6, 8, 9, 10 or 12 m). Fertilization and crop protection is often made at widths of 2, 3 or 4 times the primary working width. While CTF originally in Australia aimed to have the track width of all equipment the same, today in Europe it is often accepted that this is expensive, inconvenient and not suitable for road transport. Consequently a wider track width for combines is accepted. Besides, wider tyres are deployed to reduce the impact of traffic as all other traffic paths are cropped (often with the exception of spraying and fertilizer spreading tramlines in cereals and pathways between beds in vegetable production).

Researchers have attempted to assess the economic and environmental benefits of CTF using field experiments. From a case study for a multi-cut grass silage system in Scotland, UK, Hargreaves et al. (2017) documented that introducing CTF provides a net economic return derived from increased yields due to a reduction in compaction and sward damage. Antille et al. (2019) provided a review of the effects/implications of CTF systems on overall soil health, crop performance and yield, fertilizer and water use efficiency, and greenhouse gas emissions. As early as 1986, energy savings of approximately 50% were reported from CTF use in the Netherlands (Lamers et al., 1986). In Denmark, Gasso et al. (2014) presented the significant potential for CTF to reduce environmental impacts through reduced greenhouse gas emissions in intensively managed arable cropping systems (in the range of 20–45% for N_2O and 370–2100% for methane (CH_4) with at least 20% reduction in direct emissions from field operations.

Based on a 10 year field experiment from Loess Plateau in China, Bai et al. (2009) indicated that CTF increased mean wheat yield by 11.2%. Drawing from a case study on an Australian sugar cane farm, Halpin et al. (2008) concluded that a farming system with precision CTF and minimum tillage is more profitable than traditional practice. Using whole farm modelling in Australian dryland agriculture, Kingwell, Fuchsbichler (2011) reported that CTF would increase profit by 50% mainly through its beneficial effect on yield and crop quality. Hussein et al. (2021) reported 30% increase in sorghum yield due to CTF. Studies from Denmark and the UK showed that CTF enables a considerable reduction in headland area and input use and claimed that the overall benefits would be higher if CTF was integrated with other precision farming techniques (Tavella et al., 2010; Jensen et al., 2012).

CTF also provides other benefits such as minimizing soil runoff, economizing on input use from reduced overlaps, providing reduced operator stress with auto-steering and reducing soil-emissions (Chamen et al., 1992; Godwin et al., 2015; Pedersen et al., 2015; Vermeulen, Losada, 2009). Tullberg (2010) documented that by restricting compaction to narrow and permanent wheel tracks, CTF contributes to reducing nitrous oxide emissions which are higher in compacted soils. Tullberg et al. (2018) concluded that CTF can bring about 30–50% reduction in soil nitrous oxide and methane emissions. The benefits can potentially be higher when CTF is combined with reduced tillage or no-tillage systems and assisted by precision agriculture technologies (Antille et al., 2019).

While CTF is considered to provide multifaceted benefits as summarized above, there are also potential drawbacks associated with it. The main drawback is the investment required in suitable width-matched machinery and the associated auto-steering technology. Driving patterns must be controlled, which can have implications for field efficiency in service vehicles like grain trailers or slurry tankers which must follow the pathways rather than turning to exit the field by the shortest distance when their load cycle is complete (Bochtis et al., 2009).

CTF is compatible with EU soil protection laws and regulations aimed at preventing soil compaction. While soil is compacted in the permanent track area 70–80% of the farm area is not compacted by field traffic where CTF is deployed (Chamen, 2015). Low soil disturbance minimum tillage or no-till is more easily deployed with CTF as the soil is not subjected to traffic induced compaction. While the permanent tracks will be compacted, negative effects are limited to a small area and are more than compensated for by the lack of random traffic and intensive soil cultivation in the larger field area (Antille et al., 2019).

While experimental evidence suggests multiple benefits from CTF, its use on commercial farms is limited for various reasons such as the high cost of machinery modification (Rochecouste et al., 2015); the perception that CTF is not for small farms (Larocque, 2012); and the lack of demonstrated benefits under local conditions. Moreover, CTF demands a change of mindset towards prioritizing soil health, careful route planning and making decisions with a long-term perspective and in a holistic manner.

In Europe, soil compaction is already recognized as a threat (COM, 2006; Anon, 2008; Schjønning et al., 2018; JRC, 2016). However, CTF remains a niche activity. In the literature, the benefits of CTF in terms of yield improvement, soil health, input-use efficiency and environmental benefits are frequently reported. However, literature on the perceptions/views, knowledge and concerns relating to CTF and its adoption, of current, and of potential, CTF using farmers, is lacking.

This study intends to fill part of this gap by analyzing data from a survey of farmers, as part of adoption studies in two ICT-AGRI European projects: CTF-OptiMove (http://ict-agri.eu/node/36327) and PAM-CoBA (http://ict-agri.eu/node/36322). The primary objective is to assess and understand farmers' perceptions about CTF and related technologies; what limits them from using the technology and how they think it could be improved. The study also seeks to identify intervention approaches, relevant stakeholders, and their roles for the future development of CTF.

2. Methods

2.1. Description of survey and data

The data used in this study is from a cross sectional survey collected from January to April 2018 from 8 European countries (Belgium, UK, Netherlands, Ireland, Denmark, Germany, Sweden and France) using the network of the project participants to secure participants. The background of the farmers invited to participate in the survey varied widely across the countries. The survey was a structured questionnaire administered online using the SurveyXact platform (https://www.surveyxact.dk). An overview of the survey data is provided in Thomsen et al. (2018).

All 263 members (136 from UK, 80 from Denmark, 15 from Sweden, and 32 from other countries) of the CTF Europe association (https://ctfeurope.dk/) which includes farmers, advisors, machinery companies and others with an interest in CTF farming systems, were invited to participate. CTF Europe member farmers generally operate larger farm sizes than average in their countries.

In the Netherlands, the survey was distributed to 63 farmers, 3 were from the list in CTF Europe and the rest were members of a farmers' association in the Hoeksche Waard (HW) district who cooperated in earlier projects on in-field traffic. Compared to other regions in the Netherlands, HW member farmers are considered more advanced and early adopters.

In Belgium, the survey was distributed to approximately 2200 farmers using the sprayer inspection customer database for Flanders, administered by the Research Institute for Agriculture, Fisheries and Food (ILVO). In Ireland, the survey was distributed to 140 farmers with active email addresses from the total membership of 200 of the Irish Tillage and Land Use Society (ITLUS). ILTUS members tend to be the larger growers in the country with between 100 and 800 ha per farm. A total of 103 valid survey responses were received and used in this study.

The survey data included demographic attributes of the respondents (age and education level), farm size, machinery ownership, tillage type, concern about soil damage due to heavy machinery and remedial measures, mode of farm ownership, perception/expectation about long-term benefits from using Precision Farming (PF) & GNSS and, use of CTF practices. Survey participants who considered themselves as 'CTF-users' were asked technical, experience and expectation related questions relating to their use of CTF.

2.2. Sampling and definition issues

The survey questionnaire contained an introduction section giving background information about soil compaction and CTF. The conceptual definition of CTF provided in the introduction section was: "*Controlled Traffic Farming (CTF) is a production and management system that requires the repeated use of the same wheel track for every operation, and for all vehicles and implements to have a particular span corresponding to the base wheel track*". In this study, 'CTF user' denotes farmers' own perception of their CTF use as responded to the question "Do you use CTF" (Q19 in the questionnaire).

Two issues must be considered when analyzing the survey data. Firstly, the low response rate (about 4%) may introduce a selection bias, i.e., those farmers with prior experience with CTF technology and early adopters of mechanization technologies may have participated at a higher rate than those operating small farms and/or not considering CTF.

Secondly, there is heterogeneity in sampling across countries in the survey. Members of CTF Europe already have awareness of and are interested in CTF. The respondents from Ireland were members of a soil and tillage association that had participated in previous workshop events concerning soil compaction prevention, though not specifically CTF. However, the sample from Belgium is quite different because the criterion was owning a sprayer and only included the Flanders region with relatively small farm sizes.

2.3. Analysis method

The study used a descriptive approach to present farmers' perceptions, experiences, expectations, challenges and needs regarding CTF. Numerical data was summarized using percentages, cross-tabulations, and histograms. Responses to open-ended (free-text response) questions were summarized and explained under thematic headings. Where it was considered useful, data was disaggregated by country and/or CTF-use category.

Owing to the small sample size and sampling heterogeneity across the countries surveyed, the use of statistical analysis methods (e.g., regression) was limited. To assess the presence of statistically significant differences in mean farm size between CTF-user and non-user groups, a T-test was performed.

3. Results

3.1. Sample distribution, farm size and production type by country

The distribution of survey respondents, farm size and production type is presented by country in Table 1. Most of the respondents were from Belgium, Ireland, the UK and the Netherlands. In terms of proportion of CTF-users, the UK sample ranks first (44%) followed by Ireland and Belgium (13% each). Because of their very small representation, samples from Germany, France, Canada (1 respondent from each) and Sweden (2 respondents) are grouped together as 'Others'.

In Table 1 summary statistics for total farm size and the percentage of farm area where CTF is applied is presented (Q1 and Q23 in the questionnaire).

There is a wide difference in farm size across countries. Categorizing farm area into large (>500 ha), medium (between 100 and 500 ha) and small (up to 100 ha) shows that nearly 86% of respondents from Belgium operate small farms in contrast to none for the UK sample. The majority of the respondents from Ireland and the Netherlands lie in the medium farm size category. Farm sizes are larger for the Danish and UK sample with 75% and 65% respectively greater than 500 ha. The percentage of farm area under CTF operations also differs across countries. The sample from Belgium is the lowest both in terms of farm size and the proportion under CTF practice. The UK sample features the highest values both in farm size and percentage area under CTF and this data is also from 14 CTF user farms, which is a much larger sample than from the other countries.

As shown in Table 2, there appears to be considerable difference in the type of crop/animal production respondents are involved in (Q5 in the questionnaire). For the aggregate sample, 82% of respondents said to produce one or more cereal crops, 40% onion, 37% perennial crops and 31% beet with the least proportion (10%) involved in pig production. Note that a respondent could engage in more than one type of crop and/or animal production. Cereal production is the most common for the sampled farmers with the vast majority reported to have produced one or more cereal crops (an exception is the sample from Netherland where 91% engage in onion production while 82% engaged in crop production). In UK and Ireland, all sampled farmers produce cereal crops. Pig production is the least common with only 50%, 16% and 6% of the samples from Denmark, Belgium and UK respectively involved in it. Differences in the type of production can have a significant implication for the use of CTF at its early development stage, at least. However, in the survey it was not specified on what types of production respondents apply CTF systems.

In Table 3 results from a mean equality test for farm size between the CTF-user and non-user groups are presented. There is a significant difference in mean farm size between the two groups.

The average farm area for the aggregate sample was 428 ha. CTF-users operated significantly larger average farm area (951 ha) compared to 192 ha for Non-users (see Table 3). The farm numbers were too small to show statistical differences at a country level.

3.2. Concern about traffic-induced soil compaction and minimization measures

About 77% (70% Non-users; 91% CTF-users) of respondents reported that they were concerned about heavy machinery and its potential damage both on the field headlands and the main body of the field.

Measures, other than direct adoption of CTF, being used by survey respondents to minimize traffic damage (Q9 in the questionnaire) are presented in Table 4. Values in parenthesis are percentages relating to the CTF user only subsample.

For the overall sample, the traffic damage minimization practices most used are: low ground pressure tyres on tractors and harvesters (70%); ploughing and sowing headlands last to reduce damage (67%) and; restricting grain trailers to field headlands for loading (53%). The

Table 1
Sample distribution, farm size and CTF use by country.

Country	N	Mean farm area (ha)	Farm size category			CTF users (%)	CTF area share (%)
			Large (>500 ha)	Medium (>100, <=500 ha]	Small (<=100 ha)		
Belgium	44	121	1(2)	5(11)	38(86)	9.1	61
Denmark	4	1260	3(75)	0	1(25)	75.0	87
Ireland	22	324	2(9)	15(68)	5(23)	18.2	75
Netherland	11	201	1(9)	6(55)	4(36)	27.3	92
UK	17	1142	11(65)	6(35)	0	82.4	93
Others	5	998	4(80)	1(20)	0	80.0	90
Aggregate sample	103	428	22 (21)	33 (32)	48 (47)	31	–

Note: values in parenthesis under columns 'Large', 'Medium' and 'Small' represent the percentage of observations in the respective country whose farm area lies in that farm area category. For example, respectively 86% and 2% of the observations from Belgium operate farm area up to 100 ha and above 500 ha.
'CTF area share (%)' denotes the area share where CTF is applied on the farm as responded to the question "What is the percentage of the land area you farm, where you currently apply CTF-practices?". 'CTF area share' is only for the subsample which applies CTF practices.

Table 2
Percentage of respondents by country according to the type of crops/animal they produce.

Country	Perennial	Cereal	Pig	Beef cattle	Dairy	Vegetables	Onions	Beet	Potatoes	Other production
Belgium	36	64	16	18	30	41	52	34	32	14
Denmark	50	75	50	0	0	0	0	25	50	0
Ireland	41	100	0	45	0	0	9	9	9	5
Netherland	27	82	0	0	9	27	91	73	27	73
UK	47	100	6	24	0	0	24	35	18	12
Others*	0	100	0	0	0	0	40	0	40	0
Average	37	82	10	21	14	20	40	31	25	17

Table 3
Difference in farm size (ha) between CTF-user and non-user groups as assessed by the mean equality test.

Group	N	Mean farm size (ha)	Std. Err.	Std. Dev.	[95% Conf. Interval]
Non-user	71	192	48	402	[97 287]
CTF-user	32	951	183	1037	[578 1325]
Combined	103	428	74	750	[282 575]
Diff		-759	142		[− 1040 − 478]
Ho: diff = 0 t = −5.3629; df = 101					
Ha: diff < 0 Ha: diff!= 0 Ha: diff > 0					
Pr(T < t) = 0.0000 Pr(|T| > |t|) = 0.0000 Pr(T > t) = 1.0000					

Diff =mean(Non-user) - mean(CTF-user); df= degrees of freedom; t = T-value; N = number of observations; Std. Err.=Standard error; Std. Dev= Standard Deviation: Ho=Null hypothesis; Ha= alternative hypothesis; Pr= probability

use of low-ground pressure tyres on tractors and harvesters is the most in use both in the overall sample and the CTF-user sub-sample. Deliberately fixing tramlines to minimize soil damage is moderately used when assessed for the total sample, but the second most used practice for CTF-users. On the other hand, changing field turning headland to different parts (19%) and the use of dedicated crop transfer trailers ('Chaser bin') fitted with large tyres (22%) are the least used. When future adoption was considered, selection of smaller machines (27%), selection of trailed equipment to reduce axle load (22%) and fixing tramlines (20%) are ranked highest. Half of the respondents use a combination of three or four of the nine damage minimization techniques listed in Table 4.

CTF-users seem to use a combination of more techniques to minimize traffic-induced damage on their soil compared to the 'Non-users' group where about 34% of the CTF-users and 23% of non-users apply a combination of five or more of the damage minimization techniques. Regarding crop establishment system, CTF-users employed reduced/strip-tillage (44%) and no-till (31%) whereas the majority (82%) of Non-users practiced plough-based cultivation.

Table 4
Machinery traffic minimization strategies of all and CTF-user respondents.

Traffic damage minimization technique/ measure	Practice currently (%)	Consider for future use (%)
Low ground pressure tyres on tractors and harvesters	69.9 (84.4)	10.7 (6.3)
Chaser bin	22.3 (43.8)	11.7 (15.6)
Grain trailers restricted to field headland for loading	53.4 (53.1)	9.7 (3.1)
Headlands ploughed and sown last to reduce damage	67.0 (59.4)	6.8 (3.1)
Change turning headland to different parts of field	19.4 (15.6)	16.5 (12.5)
Select smaller machines to reduce axle load	31.1 (21.9)	27.2 (40.6)
Select trailed equipment to reduce axle load	35.9 (40.6)	22.3 (21.9)
Deliberately moving tramlines to avoid successive loading	29.1(12.5)	13.6 (12.5)
Deliberately fixing tramlines to minimize damage	42.7 (81.3)	20.4 (15.6)

Note: The values in parenthesis are only for the CTF-user group.
Note: 'Chaser bin' refers to the use of dedicated crop transfer trailers that are fitted with large tyres to transport crop from the field to road trailers which are restricted to farm roads or field headlands.

3.3. *CTF practice and service provision*

Most of the CTF-users (63%) practice CTF on their farms with their own equipment. Some provide CTF services to other farmers while others complement their CTF practice by hiring service providers for some CTF operations. Two respondents (with farm area of 3000 ha and 1300 ha, respectively) said they provide CTF services to other farmers while not applying on the farm they operate. Refer to Table SM2 in Supplementary material.

Though a generic definition of CTF was provided in the survey introduction, there may still have been subjective judgement among respondents (and possibly across countries) about what constitutes CTF. For example, 13% of 'CTF-users' said they do not use the same tramlines for fertilizer and spraying while 41% of non-users said they use the same tramlines for the two operations.

3.4. Farmers' perceptions about CTF and precision farming (PF) using GNSS

There seems to be a positive perception about CTF and PF among the surveyed farmers. About 51% of the respondents (94% CTF-users; 31% Non-users) said they would encourage other farmers to use CTF practices Table 5 summarizes responses to these questions.

The majority of respondents (74%) said they see both labor saving and environmental benefits from the use of GNSS and PF (Table SM1 in supplementary material). The expectations about long-term benefits of using GNSS and PF seem to be higher among the CTF-user group.

Responses to open-ended questions on the perceived advantages of using PF (and CTF) are summarized as follows:

- Input use efficiency: labor, nutrients, seed, fuel, machinery, optimized crop area;
- Soil health: reduced erosion, less compaction, beneficial to microorganisms in the soil, drainage;
- Less overlap of machinery passes, less traffic;
- Pollution reduction, reduced emissions, less runoff, protection of waterways;
- Improved management, less complication, improved working conditions; and
- Other potentials: possibility to incorporate other farming techniques, mechanical weed control, minimum or no-till.

3.5. Characteristics, motives, experiences, and expectations of CTF-users

CTF-users differ in the extent/level of their use of the system. About 81% of the CTF-users apply CTF practices on at least 75% of the farm area (56% apply CTF on the entire farm area). About 56% of the CTF-users have all their machinery working on permanent traffic lanes (or tramlines) whereas about 12% use seasonal CTF where harvest and primary tillage are not included in the CTF system. About 19% use the same tracks for all operations whereas about 56% use the same tracks for most crops and most machines. Most CTF-users (about 84%) use high-precision positioning system (e.g., RTK). As far as the type of RTK correction service is concerned, 63% of CTF-users use radio-based base stations (44% have own base station & 19% use a shared service) and 25% use an internet-based service (mobile phone technology). Those who do not use RTK systems rely on satellite-based augmentation signals.

The most frequently chosen motives/reasons to use CTF are to reduce damage to soil structure, improve efficiency/reduce cost, increase profit and to reduce environmental impact (refer to table SM3 in supplementary material). Expectation about the future utility of the CTF system is also an important motive. In most cases a combination of the listed factors (usually three) were reported in farmers' reasons for using CTF practices.

CTF users reported a 59% reduction in machinery operating time and 25% having more office time after introducing CTF. The majority (84%) expect CTF practices to increase crop yield on their farm. Expectations about increased long-term gross margin per hectare are also optimistic as presented in Fig. 1.

Table 5
Perceptions about CTF among all, CTF-user and non-user groups.

Question	Response	Over all (%)	Non-user (%)	CTF user (%)
Do you see any disadvantages from the use of CTF practices?	Yes	43.7	42.3	46.9
	No	35.9	32.4	43.8
	Do not know	20.4	25.4	9.4
Would you encourage other farmers to use CTF practices?	Yes	50.5	31	93.8
	No	4.9	7.0	–
	Do not know	44.7	62	6.3

3.6. Farmers' challenges and needs

Responses to open-ended questions on the disadvantages of using GNSS, PF and/or CTF highlighted: the cost of specialized equipment (purchase and/or modification of existing ones), RTK, staff training; incompatibility of machinery and navigation technologies from different manufacturers; lack of decision support tools; lack of adaptable solutions (for example, for small farms, rugged topography and root-crop harvesting); lack of suitable machinery at local contractors and/or difficulties when using contractors; other concerns such as road width limitations, and limited capacity of GNSS signals under hedges. Examples from responses to open-ended questions that relate to challenges with road width include *"adjust all machines. Roadways very fixed"; "transport width on the road"; "wide machines that are not allowed to drive on the road"*. Similarly, respondents also expressed their concerns with CTF suitability for small farm sizes (e.g., *"only suitable for large plots / areas as this requires adapted machines"; "too small plots"; "purchase price, parcel size, relative width"*).

For future development of CTF, respondents pointed out the following items and actions:

- Mechanization: Lighter, power saving, flexible, simpler (less complicated, understandable and operable) machinery; large working width, gantry system, low-ground pressure tyres;
- Standardization and compatibility of machinery and navigation technologies from different suppliers;
- Robust navigation technologies (e.g., more established GNSS systems, RTK);
- Demonstration, information campaign, research dissemination and decision support tools;
- Affordable machinery purchase and/or modification of existing machinery and RTK purchase;
- Adaptation to more farming operations (e.g., potato harvest, residue management); and
- Equipment availability through local contractors.

Some of the responses to open-ended questions about what needs to be improved for future development of CTF are directly quoted here as examples: *"better residue distribution. Extended augers that reach grain cart in 12 m CTF system"; "We need machines that are lighter and possibly more on belts."; "Accurate manufacturer description of implement width and move to slightly oversize widths eg 6.2 m, 12.4 m to allow for crabbing"; "Lower ground pressure tyres. Reduced power requirement implements"; "more evidence on yield enhancement over random traffic farming. How to integrate into a root system"; "more available equipment"; "more equipment at the contractors"*.

4. Discussion

There are wide differences in sample size, mean farm size and CTF-user proportion across countries included in the survey. Coupled with the sampling concerns of non-random selection, heterogeneity in sampling across countries, low survey response rate, and likely subjective/perceptional differences in defining CTF, this makes it difficult to make cross country comparisons and/or generalizations at country level. As the available literature eliciting real experiences and perceptions of farmers is limited, the work reported here contributes to the development of this area of research.

The surveyed farmers expressed concern about heavy machinery and the damage it causes on soil. This is in line with the evidence that soil compaction is a threat to European agriculture (ESDAC, 2008;

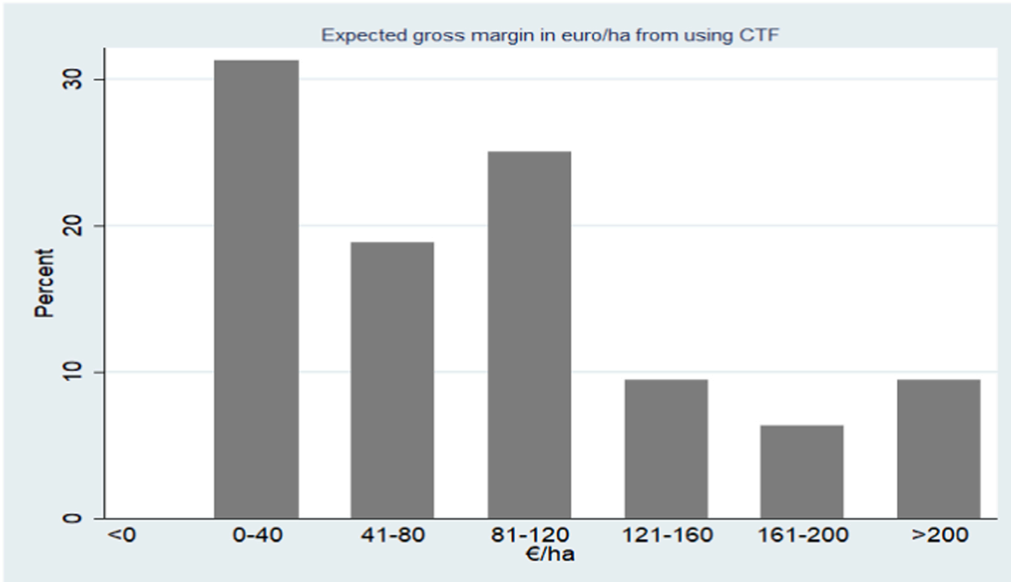

Fig. 1. The proportion of respondents that expected gross margin increases of different amounts (€/ha) following adoption of CTF.

Schjønning et al., 2018; JRC, 2016). As shown in Table 4, farmers are employing a combination of techniques to minimize damage. CTF-users seem to use a greater number of damage minimization techniques in combination, probably because this group are acutely aware of compaction issues and open to adopting a multitude of measures.

Among a list of techniques presented in Table 4, low-ground pressure tyres are the most used traffic damage minimization technique. Low ground pressure tyres have been recognized to improve topsoil conditions and crop yield (Vermeulen and Perdok, 1994). The technique is also the most in use by the CTF-user group. There can be several possible explanations for this. CTF has evolved from an approach where the pathways did not grow harvestable crop and where track widths were fixed, to a more flexible system where the base machine pathways are cropped, where some machine types have different track widths, and where varying machine weights require different tyre widths. Consequently an approach where tyres and ground pressures are chosen to limit soil stress on traffic paths and field headlands is sensible. It is also possible that many who consider themselves as CTF-users but only limit or control traffic to a limited extent, also use low pressure tyres to limit damage generally. Overall, farmers that are most conscious of potential soil damage use a combination of techniques to protect the soil.

CTF is used on larger farms with the CTF-user group on average operating nearly 5 times more area as the non-user group (Table 3) This may be a response to the need to reduce the damage risk of the heavier equipment on these farms coupled with the capacity of large farms to take advantage of economies of scale in machinery investment by amortizing fixed cost (Pierpaoli et al., 2013; Chamen 2015)). This capacity to avail of scale benefits has been documented in previous studies including other PF technologies (Tamirat et al., 2018). In the current study, this is highlighted in the UK data where farm sizes are greater and CTF adoption is more common. The large mean farm size in UK (relative to other Western European countries such as Denmark, Germany, Ireland, Belgium, Netherlands) is also docuemnted in Loughrey et al. (2016).

There are differences in the level of use of the system among the farmers who considered themselves as CTF-users, indicated by the proportion of farm area on which CTF is used. Most ‘CTF-users’ are not implementing a complete version of CTF as only 19% use the same pathways for all operations, and 56% use the same tracks/pathways for most crops and most machines. This has partly to do with subjectivities in definition of ‘CTF-user’ as described in the methods section. Partial adoption is to be expected as conversion to CTF demands several adjustments and learning through experimenting (Chamen 2015). Being conscious of the challenges of matching machine, track and tyre widths, and enabling deeper cultivation occasionally in full CTF systems, some farmers may still desire to manage their traffic by implementing some level of CTF as part of a soil management system that also includes reducing ground pressure and other soil protection measures.

An important learning is that the current market for CTF rental/contractor service appears to be very limited as most of the surveyed farmers practice CTF by their own. This could be because the technology and particularly its utility in terms of ’pay back’ is not fully proven across a range of real farm situations. Responses to open-ended questions about CTF challenges/disadvantages (e.g., “*difficult to operate when using a contractor; ”machines differ in track width with regard to contractors*”) testify farmers’ challenges with contracting.

Surveyed farmers have positive perceptions about the technical potential of CTF. A considerable proportion of farmers who do not consider themselves as CTF-users said they would recommend other farmers to use CTF (Table 5). This implies that implementation issues (e.g., difficulty in adapting to own circumstances, and perhaps lack of sufficient scale on their own farm) play a key role in adoption decisions. Overall, surveyed farmers had positive expectations about the benefits arising from using PF and CTF. Expectations about CTF adoption impact on long-term- gross margin (Fig. 1) were also optimistic. These expectations are supported by research on the effect of CTF adoption on crop yield (Hefner et al., 2019; Hussein et al., 2021) and profit (Alvemar et al., 2017; Kingwell and Fuchsbichler, 2011). Most of the surveyed farmers (59%) reported efficiency gains in machinery operating time due to CTF adoption. Optimistic expectations about labor saving and environmental benefits from using GNSS and PF were also expressed. There is already evidence of environmental benefits arising from practicing CTF in the form of reduced soil emissions (Gasso et al., 2013; Tullberg, 2010; Tullberg et al., 2018). The long-term labor saving expectation is also supported by Luhaib et al. (2017).

The main issues farmers identified in this research regarding CTF were: affordability, compatibility; lack of decision support tools; adaptability (e.g. small farms, rugged topography, and root-crop harvesting); and accessibility (lack of suitable machinery at local contractors and/or difficulties when using contractors). Machinery cost is referred to as a pressing issue limiting farmers from taking advantage of CTF systems. This issue was also identified as a major constraint in

Australia (Rochecouste et al., 2015).

Perceptions that CTF is not suited for small farms are holding back European farmers from taking advantage of the technology, as was similarly noted by Larocque (2012) for western Canadian farmers. Examples from farmers' responses to the open-ended questions about CTF challenges/disadvantages such as *"cost of matching equipment", "cost of machine renewal", "cost of operations", "big investments to get everything on the same track and working width, "too expensive",* etc. exemplify the seriousness of the issue. Future availability of optimized turning paths and optimized field pathways to be implemented via auto-steer systems, in combination with low ground pressure and partially controlled traffic on headlands may be an alternative particularly for smaller farms. From the responses relating to the adoption of traffic damage limitation measures, traffic management measures that combine elements of CTF with other soil protection measures may have a role on many farms. If autonomous vehicles develop and take out the need for labour, machines may get smaller and their traffic issues would be more easily resolved with lower pressure tyres.

Farmers in this study also emphasized the need for adaptable/flexible/simple machinery, compatibility among products from different suppliers, evidence of the utility of CTF systems under local conditions, decision support tools, and affordable purchase and modification solutions.

Based on the main findings, the following areas are identified as critical interventions to improve uptake and direct the future development of CTF technology:

- Develop and provide decision support tools based on region-relevant research;
- Adapt technology design to farms of differing sizes and topography;
- Engage the farm machinery industry constructively (Tullberg, 2010) and incorporate farmers' needs and views;
- Design and implement market models that reduce cost and improve accessibility of machinery/service (e.g., through farmers associations);
- Harmonize machine guidance systems and machine track widths;
- Provide incentives to those who act sustainably as recommended in (Antille et al., 2016).

Table 6 elaborates on the suggested interventions by identifying key stakeholders and intervention approaches/mechanisms for future development of CTF in the context studied.

5. Conclusions

The surveyed farmers were aware of the importance of traffic management systems and their role in limiting the potential for soil structural damage caused by heavy machinery. The participants, whether CTF users or not, were also positive about the potential of CTF adoption to contribute to better economic and environmental outcomes. However adoption levels of CTF remain very low and participants cited implementation issues as major constraints. There is a need to demonstrate the utility of CTF across a range of farming systems, scales and regions, using cost-benefit approaches based on research, adoption practice and costings that are appropriate for the regions being considered. The survey responses also indicate the need to consider a range of soil protection actions to prevent traffic damage as depending on farming systems, soils, scale, climate and other factors. The optimum soil protection solution may be a blending of CTF with other measures to suit individual farming circumstances. Accordingly, a proactive and coordinated approach involving all actors from policy makers to users, is necessary to develop sustainable and adaptable traffic management approaches to protect our soils.

Table 6
Concerns, suggested interventions and relevant stakeholders for future CTF development.

Concerns	Suggested interventions	Stakeholders	Approaches
Affordability	regulations, incentives	manufacturers, government	Reasonable pricing and/or flexible/long-term payment schemes for machinery/implement and service purchases Provide reference price information Clearly defined and widely communicated rules and regulations
Machinery rigidity	innovative engineering	manufacturers	Designing multi-purpose and adjustable machinery components
Demonstrated benefits	demonstration/research dissemination	research institutions, farm advisers, farming associations	Research outputs (e.g. more field trials in relation to soil compaction on different soil types) summarized in non-technical terms and made available/accessible to farmers Demonstration events to farmers in locality
	experience sharing	farmer networks (associations)	Organize and facilitate events for farmers to share experience with peers
	tailored extension service	extension/advisory service providers	-Expand availability of a range of extension services for farmers with favorable terms -Adapt extension services to particular needs of farmers
Accessibility	adapted economic/market/ model	research institutions, contractors, farming associations, consultancy	-Study, design and communicate alternative market models -Offer a range of flexible market models for farmers to choose fitting solutions for their context
Compatibility	standardization: regulations/incentives	government	Incentives (e.g., environmental stewardship, subsidies and/or tax exemptions) for manufacturers who involve in and/or collaborate efforts in producing standardized solutions that can be compatible with solutions/implements from different providers
		manufacturers	Dialogue and action among

(continued on next page)

Table 6 (*continued*)

Concerns	Suggested interventions	Stakeholders	Approaches
	collaborated action towards standardization		manufacturers on co-creation and implementation of standardized/ compatible solutions
Decision support tools	targeted research & Decision Support System (DSS) products/services	research institutions, manufacturers, Ag service providers	Study farmer challenges, design and provide relevant DSS solutions Adapt design, production, provision and follow up of DSS service against existing and expected challenges and opportunities
	promote research on CTF and DSS	government	Encourage (e.g., through funding) research projects that intend to develop innovative/ relevant DSS solutions,
	Develop route planning systems	research institutions & Ag service providers	Update and innovate route planning algorithms, practices and standards
Adaptability	flexible equipment	manufacturers, Ag service providers	Engage farmers' perceptions, experiences, needs, challenges and ideas throughout machinery/service design, supply and monitoring

DSS=decision support system; Ag service= agricultural service

Data statement

Research data used for this article is not available for sharing due to confidentiality.

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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.

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Appendix A. Supporting information

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