Title

Moving beyond reductive qualitative tillage labels: quantifying tillage intensity to assess soil disturbance and its impact on soil quality

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Abstract

Tillage is a generic term describing an array of practices used to prepare the soil prior to sowing crops, with a highly variable impact on soil quality. Tillage is commonly described using qualitative labels such as 'conventional', 'reduced', or 'no-till', but these denominations do not allow for quantification of the intensity of the tillage operations, and mask large differences in soil disturbance. This current study demonstrates the use of the Soil Tillage Intensity Rating (STIR), developed by the USDA Natural Resources Conservation Service, to quantify tillage intensity across research and extension contexts. Using three case studies and literature review, we show that STIR provides a consistent quantitative indicator of soil disturbance. 1. In a 45-year long-term tillage experiment, STIR effectively discriminated among treatments and captured historical changes in machinery and practice better than categorical labels. 2. On 60 Swiss wheat fields, STIR values ranged from 18 to 200 and showed large variability within and between conventional, organic and no-till cropping systems. 3. In participatory workshops with 25 farmers, STIR enabled quantitative comparison of tillage strategies and supported discussions on how to create soil-friendly rotations. Despite limitations in data requirements and local adaptation, STIR proved a versatile indicator linking tillage intensity with soil management outcomes. Its broader adoption could improve quantitative comparability among studies, enhance participatory research, and promote more transparent assessment of soil disturbance intensity and of the impact of tillage on the environment.

Keywords: STIR, soil management, soil health, tillage implements, soil disturbance, RUSLE2

1. Introduction

Tillage refers to a diversity of mechanical preparation of agricultural soils. It is an old and traditional practice, that is used for example to prepare the seedbed prior to drilling crops, to control weeds, or to incorporate crop residues and organic amendments. According to Derpsch et al. (2024), the five top reasons to justify the use of tillage are to 1. plant seeds/seedlings, 2. remove a crust, 3. reduce compaction, 4. improve water infiltration and 5. remove vegetation and control weeds. Tillage induces a disturbance of the soil, that can be more or less important depending on the type of tillage. While tillage is still the main mode of cultivation and brings many benefits, for example in terms of weed control (e.g. Melander et al., 2013), it has also been shown to have negative impacts, for example on soil structure (e.g. Büchi et al., 2022) and soil fauna (e.g. Betancur-Corredor et al., 2022). For this reason, a movement towards reduction of the intensity of tillage has gained traction in the past 50 years, originally coming as a reaction to the dramatic wind erosion coming from ploughed arable lands in the 1930s in the US ('dust bowl') (Derpsch et al., 2024). The traditional way of land preparation using a mouldboard plough as primary tillage implement is often referred to as 'conventional tillage'. Many alternatives to conventional tillage exist, with many different names, some overlapping in their meaning (Table 1). For example, the EU agri-environmental monitoring uses three main categories of tillage practices, conventional, conservation and zero tillage (Eurostat, 2020). Conservation tillage is usually defined as leaving at least 30% of residues at the soil surface, it is sometimes used as a synonym for minimum or reduced tillage, or as an umbrella term for different type of tillage such as strip till and no-till. Zero tillage, or no-till, or direct seeding, is an approach that does not involve any tillage operations, except for the sowing of the crop, done directly into the soil without prior mechanical preparation.

While conventional tillage, usually involving inversion tillage, is relatively well defined and does not create much debate, the terms 'minimum', 'reduced', 'conservation' tillage or 'no' till have many different definitions (Gonzalez-Sanchez et al., 2015, Ighodaro et al., 2020, Malone & Polyakov, 2020). These discrete categories, because of their vague definitions, hide a complex reality spanning a wide range of practices, tillage operations and implements and thus of tillage intensity. Conventional tillage is usually understood as involving mouldboard ploughing, that operates by inverting blocks of soil, thus inverting soil layers, and thus belongs to the 'inversion tillage' category. By contrast, the other type of tillage usually involve tillage implements like chisel plough, harrows, that mix or disturb the soil without inverting it. These are referred to as 'non-inversion tillage', and are seen as less intensive. Tillage for mechanical weeding is also usually lighter but more frequent. Tillage implements can also be operated at different speed and depth, and some may be active (powered by the tractor power take-off shaft) or passive, used at the same time in a combined operation or one after the other, at different frequency, with different tractors, etc. All this will influence the impact of the operations on the soil structure and health. In addition, the soil characteristics themselves, in particular texture, soil humidity, and the conditions under which the tillage is done will also interact with the type of tillage and determine the impact on the soil properties. For those reasons, the use of broad, qualitative tillage categories and labels to investigate the impact of tillage on crops or soil properties is reductive and has limited mechanical explanatory power. It also makes comparisons between single machines, ways of utilisation, cropping techniques, rotations and systems difficult, and bring uncertainties in meta-analyses on soil tillage. To our knowledge, only one quantitative index of tillage intensity has been developed, and is the focus of this study.

In the United States, the Natural Resources Conservation Service (NRCS), part of the USDA, has developed a method to quantify the intensity of soil tillage, called the Soil Tillage

Intensity Rating, STIR (USDA-NRCS, 2008). This method is mainly implemented within the Revised Universal Soil Loss Equation 2 (RUSLE2) method and software to take into account the impact of tillage on erosion risk, but is also widely used as a standalone by US agricultural extension services. The adoption of this method for research is almost non-existent, while it offers a unique way to quantify soil tillage intensity. Moving from a qualitative classification of tillage to a quantitative index would offer better insights for comparing practices across farms and across studies. The aim of our study is to present the STIR method and its application to research using three case studies. We hypothesise that a quantitative assessment of tillage intensity using the STIR method provides greater analytical power and comparability than usual categorical classifications of tillage practices. Specifically, we test whether STIR 1. better discriminates tillage treatments and temporal changes in a long-term experiment, 2. captures within- and among-farm variability in soil disturbance more accurately than qualitative labels, and 3. supports participatory learning by enabling farmers to quantify and discuss the impact of their management practices on soil. This study is methodological in nature. Rather than testing specific hypotheses and establishing statistical significance, it illustrates how the STIR can be applied in diverse research and participatory contexts. Quantitative comparisons are presented descriptively to demonstrate the analytical potential and interpretative value of STIR. Through these case studies, we aim to demonstrate how adopting a quantitative indicator of tillage intensity can generate new insights into the relationships between tillage, soil quality, and management decisions. This study shows how the STIR can be used beyond its original implementation in erosion modelling towards a broader research and knowledge-exchange framework for soil conservation.

2. Material and Methods

2.1 Soil Tillage Intensity Rating STIR

To calculate the Soil Tillage Intensity Rating (STIR), a tillage intensity score is attributed to each type of tillage implement or operation as a function of four factors: 1. operating speed, 2. tillage type, 3. tillage depth, 4. surface area disturbed. The score for any operation is then calculated according to the following formula (USDA, 2012):

STIR[mph, inch] = (0.5 x speed) x (3.25 x tillage type) x depth x surface

or STIR[km/h, cm] = (0.3107 x speed) x (3.25 x tillage type) x (0.3937 x depth) x surface

Operating speed: represents the speed at which the tillage operation is done, a higher speed having more impact on the soil than lower speed. The STIR values listed in RUSLE2 are based on the operating speed recommended by machine manufacturers.

Tillage type: this is a coefficient representing the type of soil disturbance induced by the implement. The possible values are pre-determined: 1.0: inversion and some mixing (e.g. mouldboard plough), 0.8: mixing and some inversion (e.g. chisel plough, field cultivator), 0.7: mixing only (e.g. rotary tiller), 0.4: lifting and fracturing (e.g. subsoiler, manure injector), 0.15: compression (e.g. rollers).

Tillage depth: the depth at which the soil disturbed.

Surface area disturbed: represents the proportion of the soil surface that is disturbed by the tillage operation. In the case of a mouldboard plough it is equal to 1 (100% of the surface is disturbed), while for some no-till drills it can be as low as 0.1 (10% of the surface is disturbed).

The RUSLE2 documentation offers a long list of operations with predefined STIR scores (Table 2), that can be used as such, or new values can be calculated according to the above formula. The score of each operation is then summed for all interventions done during the cultivation of an arable crop between harvest of the preceding crop and harvest of the main crop (e.g. seedbed preparation, weeding) to obtain a total score, usually falling between 0 and 200. It can also be calculated at the rotation or farm scale. The higher the total score, the higher the soil disturbance.

2.2 Data analysis

2.2.1 Case study 1: STIR for characterising tillage treatments in a long term experiment

This first case study is based on a long-term soil tillage experiment, set up in 1969 by Agroscope in Changins (46°24′ N, 06°14′ E, 430 m above sea level), Switzerland (Büchi et al., 2017). The experiment compares four different types of tillage, T1. conventional inversion tillage (20-30 cm), based on mouldboard plough; T2. deep non-inversion tillage (25-30 cm), mainly based on the use of a chisel plough, converted to no-till in 2007; T3. shallow non-inversion tillage (10-15 cm), using a cultivator, and T4. minimum tillage (5-10 cm). Using the historic records of the tillage operations between 1969 and 2013, we calculated, for each crop year and treatment the number of interventions per crop year and the corresponding total STIR score using the individual tillage implement scores from RUSLE2, as explained in section 2.1.

2.2.2 Case study 2: STIR for characterising on-farm tillage intensity in conventional, no-till and organic wheat cultivation

This second case study is based on an on-farm assessment of the impact of cropping systems and practices on crop production and soil health, that was conducted in Switzerland in 2016 (Büchi et al., 2019, Büchi et al., 2022). Information about tillage practices was collected for 60 different fields (each on a different farm), all growing winter wheat during the year of sampling. For each field, the total STIR score on the period from the harvest of the previous crop to the harvest of the wheat was calculated using the RUSLE2 values, including seedbed preparation, sowing, mechanical weeding but excluding the harvest of the winter wheat in 2016. Standard depth and speed of operations were used. In addition, the number of tillage and mechanical weeding operations during the same period was also calculated. Soil sampling was done in all fields in spring 2016, with a manual auger, to a depth of 50 cm. Composite soil samples (15-20 cores per field) were used to represent each sampled field. Among other properties, soil organic carbon (SOC, Loss on Ignition method) was determined for each field (see Büchi et al., 2022 for a full description of the methods). Here we investigated the correlations between the STIR score and the number of interventions and how they correlated with SOC.

2.2.3 Case study 3: STIR as a tool for participatory engagement and knowledge exchange with farmers on tillage and soil health

This third case study is based on a participatory project ('Progrès Sol') with 25 farmers conducted by FiBL (Research Institute of Organic Agriculture) and Pro Conseil (extension service) in Switzerland between 2017 and 2022. The participating farmers were all interested in learning more about soil health and interested in engaging in discussions around tillage and tools. In a first step, a selection of tillage implements relevant for the Swiss context was made by the project lead and two farmers, from the RUSLE2 database. A reference value for typical usage in local agricultural systems was then attributed to each implement. A simple tool was then built with farmers to calculate the STIR value at crop or farm level with the possibility to adjust the STIR reference score according to their practice in terms of depth and speed. Then a workshop was organised with the farmers to discuss the outcomes of their calculations, the method and possible improvement. A main question that was addressed during the workshop was about the impact of many light mechanical weeding events compared to less frequent but more intense disturbance such as ploughing, and about crop rotation adjustments between soil quality depleting (e.g. root crops) and regenerating (e.g. rotational leys) crops.

2.2.4 STIR in peer-reviewed literature

To further illustrate how the STIR method could be used for research purpose, we conducted a literature review using Web of Science (Clarivate) and Scopus (Elsevier) on the 27th of June 2025, using the search string "soil tillage intensity rating" with the 'All fields' option in WoS and Scopus. We also screened the references in the found records to identify potential additional articles to include in our review.

3. Results and Discussion

3.1 Case study 1: STIR for characterising tillage treatments in a long-term experiment

During the period from 1969 to 2013, while the tillage treatments retained the same labels, the number of tillage operations and the implements used changed, to adapt to evolving material, pesticides and practices (Figure 1A). At the same time, the total STIR for each treatment also changed, but showed overall more stability than the number of operations (Figure 1B). This indicates that STIR provides a more process-oriented representation of soil disturbance, than what is permitted by the count of traffic operations. For this experiment, the STIR scores discriminated the four tillage treatments more clearly than the number of operations (Figure 1C & 1D). In addition, overlap between the STIR scores between treatments showed that using the treatment names as basis to compare the effect of tillage on soil may not allow capturing the nuance that a quantitative assessment like STIR could offer. These findings demonstrate that applying STIR to long-term experiments captures management adaptation over time. In such datasets, STIR adds interpretative value by enabling quantitative comparison even when the operational details evolve. However, historical implementation of STIR remains constrained by the availability of detailed records on implements and operations, underlining the need for consistent tillage documentation in long-term experiments.

3.2 Case study 2: STIR for characterising on-farm tillage intensity in conventional, no-till and organic farming systems

In this study, the STIR score calculated in 60 different farms ranged from 18 up to 200 for a same winter wheat crop within a fairly limited geographic and climatic range, revealing large differences in actual soil disturbance. To give an example, the STIR score for a field where a mouldboard plough is used at 20 cm, followed by a rototiller and drilling using a combine seeder would lead to a STIR score of 103 (see Table 2). Such variation reflected contrasts in implement type, tillage depth, and the number of passes, underscoring how local management decisions strongly influence soil disturbance. High within system variance was also shown for organic and conventional farms, while obviously no-till farms showed more consistent scores (Büchi et al., 2019). This shows the high sensitivity of the STIR for differentiating on-farm field management within and among cropping systems.

However, in this study, and in contrast to Case study 1, the STIR scores correlated highly with the total number of tillage and weeding interventions ($r=0.8$, $p<0.001$). This indicates that, under on-farm conditions with very diverse management, frequency of interventions remains a dominant driver of soil disturbance. However, STIR also captures additional information, such as tillage depth and soil mixing intensity, that the number of interventions overlook, providing a more mechanistic interpretation of tillage. The absence of a direct correlation between STIR and soil organic carbon (SOC) at any depth shows that a unique indicator such as STIR is not enough to capture complex soil properties, that depend also on other factors such as carbon inputs. Overall, this case study demonstrates that STIR is an effective quantitative tool for benchmarking and comparing on-farm tillage intensity in very diverse cropping systems, while also revealing its limitations when used as a stand-alone proxy for soil quality.

3.3 Case study 3: STIR as a tool for participatory engagement and knowledge exchange with farmers

A first result coming out of the participatory project with farmers was that the organic farmers tended to have a higher total soil tillage intensity rating than conventional farmers due to cropping systems requiring more mechanical interventions: destruction of rotational leys, incorporation of organic amendments, mechanical weeding. However, substantial variability and overlap between the two groups were observed, with some organic farmers having lower STIR score than some conventional ones. Discussions among farmers around those results highlighted how different machines and practices have major impact on the STIR score compared to others. The participatory workshops showed that STIR provided a common quantitative language for farmers and advisers to discuss soil disturbance and management options beyond labels. Visualising their own STIR scores enabled farmers to identify which operations contributed most to overall disturbance. It also allowed farmers to compare scenarios in terms of impact on the total STIR, for example by understanding the impact of speed and depth on the soil disturbance. This iterative learning process demonstrated that STIR serves not only as a diagnostic tool but also as a catalyst for behavioural change. Some farmers changed their practice afterwards or trialled different options, guided by the calculation of the STIR and by discussions with the other farmers. Average STIR scores for the different crops grown by the farmers were also calculated and discussed. The possibility to alternate different crops according to their STIR intensity was discussed in terms of crop rotation organisation (Figure 2) and soil regeneration, as some root crops may induce important soil disturbance for their planting (potato) or for their harvest (potato, sugar beet). Farmers were then able also to compare different strategies to minimise the impact on soil over several years. Strategies to decrease the overall STIR score included, for example, running a full rotation with minimum tillage or alternating high soil disturbance crops such as potatoes with 3 years of rotational leys (Figure 2). Such examples illustrate how STIR supports reflective decision-making grounded in quantifiable evidence rather than qualitative perceptions of "intensive" or "conservation" tillage. Beyond individual practice change, the exercise also revealed methodological insights: when co-developed with users, quantitative indices like STIR can bridge scientific and experiential knowledge, fostering mutual understanding of soil processes. This participatory application therefore expands the methodological scope of STIR, from an analytical index to an interactive framework for farmer-led soil management innovation. The STIR tool developed during this project is available at www.progres-sol.ch/stir.html (French only).

3.4 STIR in peer-reviewed literature

Only three records were found when conducting a search on Web of Science, while 28 records were found on Scopus. From the three records from WoS, one came from the US (Karlen et al., 2008), one from Spain (Champagne et al., 2021) and one from Switzerland (Masson et al., 2024). From the 28 Scopus records, 18 used the STIR method, including the three also found on WoS, while 10 only mentioned it. Among those 18 articles, only three records where not coming from the US, the two already mentioned and another article from Switzerland (Heller et al., 2025). This latter article cited two more studies using the STIR method, one from the US and one from Switzerland. Three additional articles from Switzerland are the ones used in the case studies above (Büchi et al., 2017, 2019, 2022), but they did not appear in the literature search. This shows that while the STIR method is widely used by US extension services, and thus numerous scientific and grey literature can be found online, it has until now only limited visibility in the rest of the world and in particular in European research and literature.

3.5 Limitations and Future developments and usage

From the three case studies presented here, and the literature review, we demonstrated how the STIR method can provide farmers, practitioners and researchers with a very valuable tool to estimate the impact of tillage and other interventions on soil. The method is fairly easy to use and can be adapted to local needs. It can be used to create different scenarios about the settings of machines, crop and rotation management to foster discussion around the impact of management on soils. The physical impact of repetitive mechanical weeding can be quantified and more objectively assessed. However, some limitations to the use of this method currently exist.

A first caveat of the method is that the rationale and calculations behind the coefficients used in the STIR formula could not be found in the available documentation. The share of affected surface and the proportional effect of the depth of tillage seem straightforward parameters, however, the weighing of speed and type of tillage would need more clarification. In addition, as this method was developed for the US, using it in other regions requires some work to translate the tillage implements name and standard use to each local context.

Another limitation is the high data requirements if the method is applied on a large time scale, as precise information on the history of interventions and implements used is needed. Also in some cases, simpler estimate of tillage intensity can be as informative in explaining some soil properties than the more complex and data intensive STIR.

Another limitation, that was identified during discussions with farmers, is the lack of consideration for the conditions in which the work is done. For example, the soil type and moisture levels, or the soil cover by mulch or living plants at the time of the intervention may have an important effect on the resulting disturbance. The farmers suggested that the inclusion of an additional factor to fine tune the STIR as a function of those conditions could be useful in future developments. Another technical issue raised by farmers was the absence of information regarding so-called ‘active’ weeding and tillage implements (powered by the tractor power take-off shaft). In addition to the speed of the tractor pulling such implement, consideration of the speed of the powered tool itself should be included in the calculation, as it will have additional impact on the soil.

Overall, the use of STIR as a tool for participatory approaches on soil improving cropping practices was successful, but it could be improved by creating local references for STIR scores for different type of crops according to farming systems and regions, to give farmers more agency in using the tool by themselves.

3.6 Conclusion

This study demonstrates how the Soil Tillage Intensity Rating (STIR) can be applied as a quantitative indicator of soil disturbance across experimental, on-farm, and participatory research contexts to better understand the role and impact of tillage on soil quality. Unlike reductive qualitative classifications, STIR provides a reproducible and transferable index that discriminates tillage intensity more consistently and enables meaningful comparison of management systems and time periods. The high variability observed across farms and systems confirms both the complexity of tillage practices and the sensitivity of the STIR index to management diversity.

The calculation of STIR scores over long time periods is data-intensive, requiring detailed historical records of each tillage implement used, yet it allows retrospective analyses of how technical and management changes can influence soil quality. STIR offers a quantitative bridge between research and practice by allowing farmers and advisers to assess and communicate the soil disturbance associated with their tillage strategies, beyond reductive qualitative labels. The quantitative patterns identified across the three case studies illustrate the analytical potential of STIR to capture variation in tillage intensity and to generate testable hypotheses for future research.

Broader application of this approach could facilitate meta-analyses and cross-study comparisons that remain difficult with categorical tillage labels. Overall, our study shows how STIR can be used for agricultural research and extension, towards a flexible methodological tool for quantifying soil disturbance, guiding experimental design, and supporting participatory learning with farmers and advisers. Future developments should aim to refine the index by integrating local conditions and powered implement parameters to enhance transferability and predictive value across diverse agricultural systems and to make the best use of the potential of STIR for research purpose and knowledge exchange.

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Table and Figure legends

Table 1. Tillage categories used in literature, with their frequency of occurrence in scientific literature, access from Web of Science on the 27th of June 2025. For all terms, in addition to the specific tillage keyword, the search string also included (arable OR agricult* OR farm* OR crop* OR cultivat*) to ensure only references relevant to agriculture were retrieved, following Haddaway et al. (2017). The search term 'till*' was used to cover both 'till' and 'tillage' variants of the concepts.

Table 2. Examples of STIR scores for different tillage operations, from RUSLE2 database.

Figure 1. Evolution through time of the number of interventions and the STIR score for four different tillage treatments in a long-term experiment started in 1969. A. Evolution of the number of tillage interventions in each treatment. B. Evolution of the STIR score in each treatment. C. Comparison of the total number of interventions in each treatment. D. Comparison of the STIR score in each treatment.

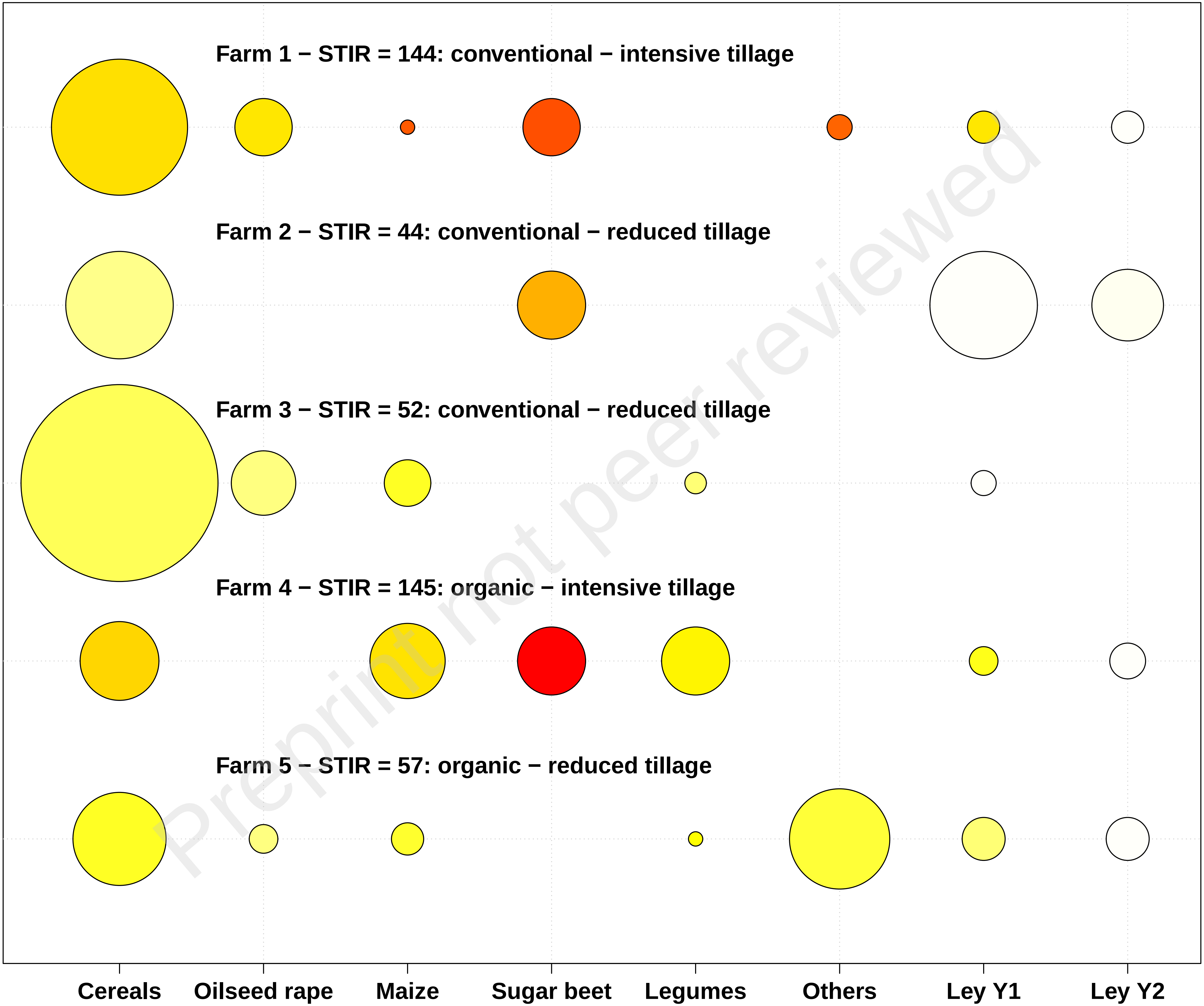
Figure 2. Examples of STIR scores at farm level, and how the presence of crops with high STIR values, such as sugar beet, can be compensated by the cultivation of other crops with lower STIR, such as rotational leys. STIR scores are shown for five different farms, conventional and organic. The bubble radii are proportional to the relative area of the crops on the farm, and the bubble colour represents the STIR score of the crops and associated cropping practices, with high values in red, and low values in white.

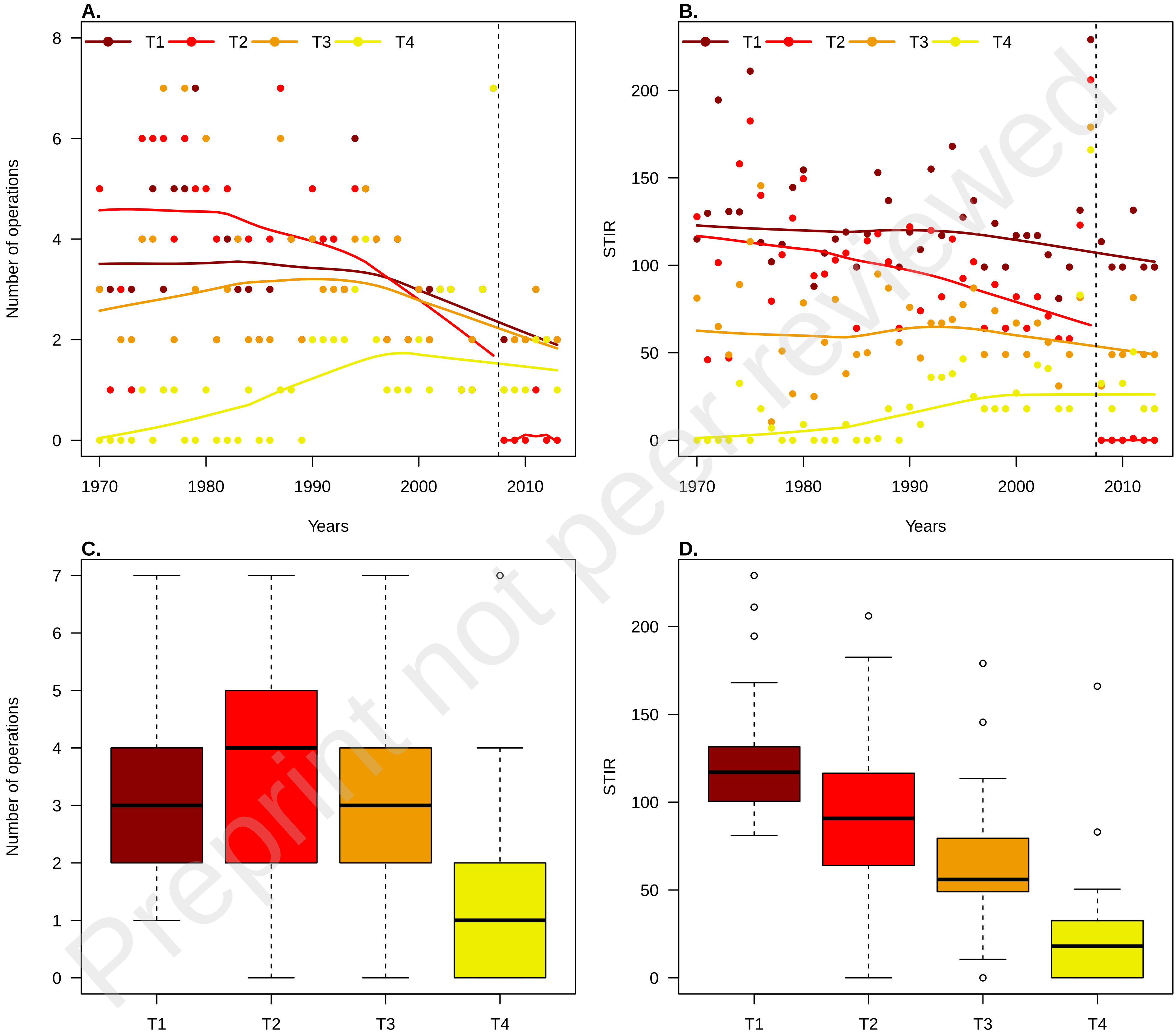
Table 1

Tillage categories/labels	Nb occurrences
tillage	65,676
conventional tillage	7,678
inversion tillage	256
non-inversion tillage	152
reduced tillage	3,579
minimum tillage	1,912
conservation tillage	5,588
strip till	707
ridge till	484
mulch till	136
vertical tillage	39
no till	16,860
zero tillage	2,029
direct seeding/drilling/sowing	2,560

Table 2

Operation	Details	Speed	Depth	Surface	Type	STIR
Mouldboard plough	depth 10 in / 25 cm	5	10	1	1	81.3
Mouldboard plough	depth 8 in / 20 cm	5	8	1	1	65
Chisel plough	with straight points, depth 15 in / 38 cm	4	15	1	0.8	78
Chisel plough	with straight points, sweeps, or twisted shovels, depth 7 in	5	7	1	0.8	45.5
Heavy or offset disk	depth 12-15 in / 30-38 cm	5 / 4	12 / 15	1	0.8	78
Heavy or offset disk	at 6-8 inch depth + corrugated roller packer	-	-	-	-	41
Subsoiler or Vee ripper		4.5	15	0.75	0.4	32.9
Field cultivator	with spike points	6	4	1	0.8	31.2
Disk tandem	light finishing	5	3	1	0.8	19.5
Rototiller	at full width, no growing crop	4	4	1	0.7	18.2
Rototiller, row cultivator	for weed control in growing crop	3	3	0.85	0.7	8.7
Cultivator	row, 1st pass ridge till	5	3	0.9	0.8	18
Rotary hoe		10	1.5	0.85	0.8	17
Harrow	coiled tine	6	2	1	0.8	16
Harrow	coiled tine, for weed control in growing crop	6	1	1	0.8	7.8
Combine seeder	rototiller + drill with single disk opener	-	-	-	-	20.6
Direct seeder	drill, heavy, double disk openers with row cleaners	5	3	0.9	0.8	18
Drill or air seeder	with double disk openers	5	1.5	0.65	0.8	6.3
Drill or air seeder	with single disk	5	0.25	0.15	0.8	2.4
Strip till		5	2.5	0.3	0.8	4.9
Manure injector	low disturbance	4	6	0.3	0.4	4.7
Corrugated packer roller		4	1.5	1	0.15	1.5


Farm 1 − STIR = 144: conventional − intensive tillage
Farm 2 − STIR = 44: conventional − reduced tillage
Farm 3 − STIR = 52: conventional − reduced tillage
Farm 4 − STIR = 145: organic − intensive tillage
Farm 5 − STIR = 57: organic − reduced tillage
Cereals
Oilseed rape
Maize
Sugar beet
Legumes
Others
Ley Y1
Ley Y2


A.
B.
C.
D.
T1
T2
T3
T4
Number of operations
STIR
Years
1970
1980
1990
2000
2010