The QuantiSlakeTest, ~~dynamic weighting of~~ measuring soil ~~under water to measure soil~~ structural stability by dynamic underwater weighing

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Abstract. We evaluated the performance of a new, simple test to evaluate soil structural stability. The QuantiSlakeTest (QST) consists in a quantitative approach of the slake test, a dynamic ~~weighting~~ weighing of a dried structured soil sample once immersed in water. The objective of this work was threefold: we aimed to (i) derive indicators from QST curves to evaluate soil structural stability~~regarding the underlying mechanisms of soil disaggregation~~; (ii) establish the relationship between soil properties and QST indicators; and (iii) assess how QST indicators respond to contrasting soil management practices. To meet these goals, we sampled the soil of 35 plots from three long-term field trials in the silt loam region of Belgium dealing respectively with contrasting organic matter inputs, tillage ~~treatments~~ and P-K fertilisation~~, respectively~~. For each plot, ~~QST curves~~ indicators calculated from QST curves (e. g. total relative mass loss, disaggregation speed, time to meet a threshold values of mass loss, . . .) were compared to the results of the three tests of Le Bissonnais ~~, targeting specific mechanisms of soil disaggregation~~(1996), used as a reference method for the measurement of soil aggregate stability.

Shortly after immersion in water, soil mass increases due to the rapid replacement of air by water in soil porosity. Then soil mass reaches a maximum before decreasing, once mass loss by disaggregation exceeds mass gain by air loss. Our results confirmed that the early mass loss under water is mainly related to slaking, whereas after a longer time period, clay dispersion ~~becomes the dominant process~~ and differential swelling become the dominant processes of soil disaggregation. The overall soil structural stability was positively correlated to the soil organic carbon (SOC) content and negatively correlated to the clay content of soil. Accordingly, the SOC:clay ratio was closely related to QST indicators. Nevertheless, for a similar carbon (C) input, green manure and crop residues were more efficient in decreasing clay dispersivity and differential swelling whereas farmyard manure promoted SOC storage and was more efficient against slaking. QST curves had a strong discriminating power between reduced tillage and ploughing regardless of the indicator, as reduced tillage increases both total SOC content and root biomass in the topsoil.

The QST has several advantages. It (i) is rapid to run, (ii) doesn't require expensive equipment or consumables and (iii) provides a high density of information on both specific mechanisms of soil disaggregation and the overall soil structural

stability. As an open access program for QST data management is currently under development, the test has a strong potential for adoption by a widespread community of end-users.

1 Introduction

Soil structure is one of the main factors controlling the fertility of temperate agricultural soils subject to intensive cultivation. This is particularly true for Luvisols of the loess belt of Belgium, which are among the most productive soils of Europe and therefore have experienced a long cropping history. The high productivity of these soils is primarily related to their high plant available water storage capacity as they are deep, ~~free of rocks~~ stone-free and with a texture largely dominated by silt, up to 85 % in the topsoil. In addition, these soils developed on Quaternary loess deposited $< 170.000\,\mathrm{years}$ ago (**?**) still contain unweathered primary minerals in the subsoil, acting as a source of nutrients for plants (**?**). Their clay fraction is dominated by high activity clays, which provides a favourable cation exchange capacity for plant-available nutrient retention.

Since deforestation centuries ago, the chemical and biological fertility of these soils has increased over the course of cultivation, with topsoil pH, base saturation and earthworm activity increasing ~~under repeated~~ following repeated applications of organic and mineral ~~fertiliser application~~ fertilisers and amendments (**?**). Nevertheless, today many of these soils have ~~a poor structural~~ poor aggregate stability, which makes them particularly sensitive to physical damages such as compaction and erosion (**?**). This structural weakness is related to a silt-dominated texture and ~~exaggerated by a~~ enhanced by low soil organic matter (SOM) ~~concentration in~~ content in the topsoil. Between the 1960s and 2005, cropland soils of the loess belt of Belgium have lost $14\,\mathrm{t\,C\,ha^{-1}}$ on average, mainly caused by a shift from mixed crop-livestock farming systems towards arable farming systems, with a progressive disconnection from animal husbandry (**?**). This shift caused a decrease of farmyard manure application on cropland soil and a replacement of ~~cereal~~ cereals and temporary grasslands by spring crops such as sugar beet, potato and chicory (**?**), thereby decreasing soil organic carbon (SOC) inputs. In parallel, the overall increase in ploughing depth, diluting SOM vertically, has accentuated the decrease in SOC content in the topsoil layer (**?**). The Ap horizon of these soils has a typical SOC content of about $10\,\mathrm{g\,kg^{-1}}$ (**?**), which is clearly below the threshold value of $12\,\mathrm{g\,kg^{-1}}$ generally considered as critical for ~~structural stability~~ aggregate stability (**?**). The combination of a poor soil structural stability with an incomplete soil cover ~~in~~ during the winter and spring periods (given the high proportion of spring crops in the rotation) increases erosion risks (**?**), particularly under the growing risk of occurrence of extreme climatic events induced by climate change (**?**).

In this agricultural context, conservation tillage appears as an effective way to decrease soil susceptibility to erosion and therefore has been increasingly adopted by farmers within the last 20 years. ~~According to local farmers, the~~ The replacement of moldboard ploughing by reduced tillage operations such as stubble cultivation ~~seems to have~~ has a positive effect on soil structure and water infiltration (**??**), dramatically decreasing erosion risks (**?**). Soil erosion is governed by both rainfall characteristics and environmental factors such as slope characteristics, soil cover ~~and~~ as well as soil properties such as hydraulic conductivity and aggregate stability (**??**). Owing to the difficulty to measure soil erosion and runoff, soil aggregate stability is often used as an indicator of soil erodibility (**?**). ~~The~~

The process of soil aggregation is key to understand the factors controlling soil aggregate stability. The theory of aggregate hierarchy of **?** is widely accepted to conceptualise the internal organisation of soil aggregates. At the lowest level, elementary clay plates ($< 2\,\mu\mathrm{m}$) combine into ~~floccule or domainsof clays~~clay floccules or domains, with a degree of organisation depending on clay mineralogy (quasi-crystals > domains > assemblage, **?**). ~~Floccule and domains~~ Domains combine into clusters ($2 - 20\,\mu\mathrm{m}$) under the action of binding agents such as polyvalent cations (Al^{3+} in acidic soils and Ca^{2+} and Mg^{2+} in neutral to slightly basic soils), Fe, Al and Mn oxides and organic compounds, mainly polysaccharides from bacterial and fungal mucilages or root ~~exsudates~~ exudates (**??**). They can be very stable and contain organic acids or partially degraded bio-materials. ~~Clusters~~ These clusters combine into micro-aggregates $20 - 250\,\mu\mathrm{m}$ in size (**??**) that ~~combine themselves~~ further combine into macro-aggregates ($> 250\,\mu\mathrm{m}$) under the action of wetting and drying cycles (**?**). Roots and fungal hyphae enmeshing micro-aggregates are recognised as critical binding agents in macro-aggregates, and are therefore influenced by soil management practices such as crop rotation and tillage (**?**). Clods ($> 25\,\mathrm{mm}$) constitute the upper level of soil aggregation and are, in many agricultural soils, the result of compaction by agricultural machinery (**?**). Under disaggregating forces, ~~it is important to note that~~ the destruction of one hierarchical order automatically destroys all higher hierarchical orders (**?**).

Aggregate breakdown is controlled by four mechanisms (**??**): (i) Slaking occurs during fast-wetting of a soil and consists in the fragmentation of macro-aggregates into micro-aggregates by internal pressure exerted by air entrapment in soil porosity. (ii) Mechanical breakdown by raindrop impact, also known as splash erosion, initiates soil sealing and crusting by liberating elementary particles from soil aggregates. Its amplitude relies on raindrop ~~characteristic~~ characteristics as well as internal soil cohesion, which decreases logarithmically with increasing water content (**?**). The resistance of soil to mechanical breakdown also improves resistance to soil compaction due to traffic on the field. (iii) The breakdown by differential swelling ~~depends on~~ occurs under wet conditions and depends on both the abundance and swelling properties of clay particles in soil. Nevertheless, this process mainly plays a role at macroscopic scale and has therefore a limited effect on soil disaggregation relative to the other mechanisms (**?**). (iv) Physico-chemical or clay dispersion is the last mechanism, occurring when soil is wet. ~~This~~ Clay dispersion depends on the ionic status of the soil (ionic strength in soil solution and the exchangeable sodium percentage) as well as the mineralogy of clays. Clay dispersion jeopardises the smallest level of soil aggregation (namely quasi-crystals, domains or assemblages of clay particles) to liberate elementary particles, which deteriorates any upper level of soil aggregation (**?**).

A large number of laboratory methods exist for the measurement of soil ~~structural stability. Methods can be categorised between laboratory and field and methods . Among laboratory methods, most traditional methods~~ aggregate stability. Traditional methods are destructive and rely on the resistance of soil aggregates to fragmentation under wet, or, less often, dry conditions. Some wet fragmentation methods rely on the disaggregating power of the wetting treatment only, such as percolation stability (e.g., **??**), high Energy Moisture Content (e.g., **?**), or fast and slow wetting (e.g., **?**). Other methods in wet conditions rely on an additional energy input, such as wet sieving methods (e.g., **???**), those involving shaking or ultrasonication for clay dispersion (e.g., **??**), disaggregation by raindrop impact (e.g., **?**) or rainfall simulators (e.g., **?**). ~~More recently, promising results were obtained with non-destructive methods, such as aggregate delineation by analysis of X-ray microtomography images (?), or aggregate stability prediction by visible-near infrared (VIS-NIR) spectroscopy (?).~~

Recently, the SLAKES mobile application provided encouraging results as a tool for rapid data acquisition on soil structure~~in field conditions~~. The test relies on image recognition to measure the increase in area of a soil aggregate as it disperses in water (**???**). ~~Among field methods , a variety of visual soil assessment methods exist~~The potential of some non-destructive methods on the evaluation of soil structure and aggregation has also been revealed, such as ~~the *profil cultural* (**??**), the Peerlkamp field test (**?**), the Visual Evaluation of Soil Structure method (VESS, **?**) or the visual soil assessment method (**?**). A classification of aggregates according to their stability in water proposed by **?** is another approach that can be implemented directly on the field~~aggregate delineation by analysis of X-ray microtomography images (**?**), or aggregate stability prediction by visible-near infrared (VIS-NIR) spectroscopy (**?**).

The multiplicity of methods ~~of measurement of soil structural stability highlights the complexity of evaluation of soil structure. The~~ highlights how challenging is the measurement of soil aggregate stability. From one study to another, the preferred approach is a matter of compromise depending on (i) the ~~targeted goal~~ objective of the work (evaluation of soil structure, management of erosion or compaction risks), (ii) local conditions of soil, topography~~and climate~~ , climate and cropping (the drivers of erosion or compaction risks), (iii) the technicality, cost and delay of measurement; and (iv) the spatial scale of the soil unit to investigate.

In this work, we evaluated the performance of a new, simple test to ~~evaluate~~ measure soil structural stability, named QuantiSlakeTest (QST). ~~We propose~~ It is a quantitative approach of the slake test~~(QuantiSlakeTest, QST)~~, a visual qualitative test to illustrate the impact of soil management practices on soil structure. It consists in the dynamic ~~weighting~~ weighing of a structured soil sample ~~once immersed~~ suspended in demineralised water~~, in a 8 mm mesh basket~~. This approach has the advantage ~~to be~~ of being simple, rapid and dynamic, therefore providing a high density of information ~~all over~~ throughout the process of soil wetting and disaggregation under water.

The objective of this work was threefold: we aimed to (i) unravel the mechanisms controlling soil ~~sample~~ mass evolution under water and derive indicators from the QST curves to evaluate soil structural stability~~regarding to related mechanisms of soil disaggregation~~; (ii) ~~relate QST indicators to soil properties~~ investigate the relationship between soil properties and QST indicators, particularly SOC and clay contents; and (iii) assess how QST indicators respond to contrasting soil management practices~~influence the QST indicators~~.

To meet these goals, we sampled the soil of 35 plots from three long-term field trials of the Walloon agricultural research ~~center~~ centre (*Centre wallon de recherches agronomiques*, CRA-W) dealing ~~with contrasting farming practices in terms of tillage,~~ respectively with contrasting practices of organic matter (OM) ~~restitution~~ inputs, tillage and P-K fertilisation. For each plot, we compared the QST indicators to the mean weight diameters (MWD) and the percentage of macro-aggregates (MA, $> 200\,\mu\text{m}$) from the three tests of **?**, used as a reference method. ~~Prior to measurements, we were expecting to observe (i) a relative increase in soil structural stability for the soils under reduced tillage compared to ploughing; (ii) a decrease of soil structural stability under long-term K over-fertilisation with KCl (**?**) in the P-K mineral fertiliser trial; and (iii) an overall positive correlation between SOC content and soil structural stability across the dataset (**??????**).~~

2 ~~Material~~ Materials and methods

2.1 Description of the field trials

The ~~plots sampled for soil structural stability measurements include contrasting treatments from~~ soils under study have been subject to contrasting soil management practices for a long time in three long-term field ~~trials~~ experiments dealing with soil tillage, organic matter inputs and P-K mineral fertilisation~~. At the time of sampling in April 2019, the three trials were covered with winter wheat (*Triticum aestivum*). All field~~ , respectively. All trials are located on the agricultural ~~domain~~ station of the CRA-W in Gembloux, a town in the centre of the silt loam region of Wallonia, southern Belgium. The climate is oceanic temperate, with a mean annual temperature of $10.2°\mathrm{C}$ and a mean annual rainfall of ~~$793.4\,\mathrm{mm}$~~ $793\,\mathrm{mm}$ for the 1991-2020 period[1]. All soils are developed from loess, a silt-dominated unconsolidated and ~~free of rock~~ stone-free Quaternary sediment (**?**). Soils are classified as hortic Luvisols according to the WRB (**?**). In April 2019, when the soil sampling was carried out, the three trials were covered with winter wheat (*Triticum aestivum*).

2.1.1 Organic matter trial

The organic matter trial (OM trial, $50.560°\,\mathrm{N}$, $4.726°\,\mathrm{E}$) was set up in 1959, with the initial goal of addressing the issue of decreasing organic matter inputs (farmyard manure, crop by-products) on cropland soils of the silt loam region and related consequences on soil properties, crop yields and farm profitability (**?**). The trial includes six contrasting treatments of SOM restitution in plots of $70\,\mathrm{m} \times 10\,\mathrm{m}$, repeated six times, following a Latin square design with the blocks aligned in a row. From 1959 to 1974, the field was cropped according to a four-year rotation with sugar beet (*Beta vulgaris*) as the starter crop, followed by three years of winter cereals ~~(~~ – wheat, oat ~~, barley)~~ (*Avena sativa*), barley (*Hordeum vulgare*) – or two winter cereals ~~(~~ – wheat, barley/oat ~~)~~ – and one legume ~~(horsebean~~ – horsebean (*Vicia faba*). Cultivation cycle shifted from 1975 onwards to a three-year ~~rotation~~ sugar beet – winter wheat – winter barley rotation. Among the six treatments, three were selected for soil sampling in 18 plots, described by **?**. The 'residue exportation' (RE) treatment consists in a maximal exportation of by-products (straws and sugar beet heads and leaves) and no farmyard manure application nor green manure during the intercropping period. Since 2009 however, sugar beet heads and leaves are left on the field. The 'farmyard manure' (FYM) treatment consists in one application of 30 to $60\,\mathrm{tons\,ha^{-1}}$ of composted cattle manure once per rotation, after the harvest of the ~~last winter cereal of the rotation~~ winter barley in order to enrich the soil for the sugar beet. The last application before soil sampling occurred on the 26th of July 2017. In the 'residue restitution' (RR) treatment, all crop by-products (cereal straws and sugar beet heads and leaves) are left on the fields, and one cover crop acting as a green manure is ~~sowed~~ sown once per rotation during the intercropping period between the winter barley and the sugar beet. Cover crops were vetches (*Vicia sp.*) until 2009~~(except once mustard~~ , except (i) mustard (*Sinapis alba*) in 1980~~), phacelia~~ , (ii) phacelia (*Phacelia sp.*) in 2011 and 2014 and ~~a oat-vetch-clover mix~~ (iii) mix of oat, vetch and clover (*Trifolium sp.*) in 2017. The estimated annual total carbon (C) input amounts ~~respectively~~ to $315 \pm 76\,\mathrm{gC\,m^{-2}}$, $472 \pm 82\,\mathrm{gC\,m^{-2}}$ and $487 \pm 93\,\mathrm{gC\,m^{-2}}$ for the RE, FYM and RR treatments,

[1]https://www.meteo.be/resources/climatology/climateCity/pdf/climate_INS92142_9120_fr.pdf

respectively (?). Since the start of the trial, yearly measurements of topsoil properties ($0-25\,\mathrm{cm}$) show a drop of SOC content for the RE treatment, an increase for the FYM treatment and a ~~maintain~~ steady state for the RR treatment (?). For all treatments, ~~soil is~~ the soil has been ploughed annually with a moldboard plough.

2.1.2 Tillage trial

The soil tillage trial ($50.560°$ N, $4.727°$ E) was set up in 2004 and follows a two-year rotation ~~with winter wheat (*Triticum aestivum*) followed by~~ of winter wheat and a spring crop, generally sugar beet ~~(*Beta vulgaris*)~~ or flax (*Linum usitatissimum*), ~~alternately,~~ with an exception in 2018 where corn (*Zea mays L.*) was cultivated as spring crop. A green manure is ~~sowed~~ sown after tillage following the harvest of the cereal and destroyed during winter time before the spring crop. The trial includes four tillage treatments in plots of $24\,\mathrm{m}\,\times\,21.5\,\mathrm{m}$ repeated four times, following a Latin square design with the blocks aligned in a row. Among the four treatments~~of this trials~~, the two most contrasting ones were sampled in eight plots: (i) annual ploughing (P) ~~at~~ to a depth of $25-30\,\mathrm{cm}$ with a moldboard plough; (ii) annual reduced tillage (RT) with a spring tine cultivator tilling ~~at~~ to a depth of about $10\,\mathrm{cm}$. ~~The two treatments are repeated four times in a complete random block of split-plot type. The plots are $12\,\mathrm{m}$ wide and $21.5\,\mathrm{m}$ long.~~

2.1.3 P-K mineral fertiliser trial

The P-K mineral fertiliser trial ($50.582°$ N, $4.687°$ E) was set up in 1967, with the initial goal of assessing the effect of the rate of P and K mineral fertiliser application on crop quality and yield, nutrient exportation with harvest, soil properties and farm profitability (?). The trial comprises three levels of phosphorus (P) fertiliser (applied as superphosphate $18\,\%$ or triple superphosphate $45\,\%$) crossed with three levels of potassium (K) fertiliser (applied as KCl 40 or $60\,\%$), namely nine different treatments repeated ~~six times~~ three times in two randomized complete blocks, for a total of 54 plots of $7.5\,\mathrm{m}\,\times\,50\,\mathrm{m}$. The lower level of P and K fertilisation received no P and K mineral fertiliser since 1975 (P0 and K0). The intermediate level of fertilisation consists in balancing P and K ~~exports by application of the same amount of nutrients through mineral fertilisers~~outputs and inputs, according to the nutrient balance method (P1 and K1). The higher level of fertilisation is over-fertilised, multiplying by 2 (until 2000) or 1.5 (onwards) the amount of P ~~an~~ and K applied to the P1 and K1 treatments (P2 and K2). The last application of P-K fertilisers before soil sampling occurred on the 15 July 2016. The whole field is cropped according to a three-year rotation cycle similar to that of the organic matter trial, with sugar beet as starter crop followed by two winter cereals (winter wheat and winter barley). Since the start of the trial, the soil has not received any exogenous organic matter but all by-products (cereal straws and sugar beet heads and leaves) are left on the field to maintain sufficient SOC contents. For all treatments, soil is ploughed annually with a classic moldboard plough, except before the seeding of sugar beet in 2017 (soil was prepared by deep decompaction with a heavy tine cultivator at about $30\,\mathrm{cm}$ depth in august 2016). In this study, we ~~put the focus~~ focussed on the potential effect of contrasting levels of KCl application on soil structural stability ~~, as chlorides are known to weaken soil structure~~ (?). Therefore, we selected three repetitions of each level of K within the trial for soil sampling in 9 plots.

2.2 Soil sampling

Soils were sampled on the ~~8 and 10~~ 8th and 10th of April 2019. For each ~~plot~~ of the 35 plots previously described, six structured soil samples of $100\,\mathrm{cm}^3$ were taken with steel Kopecky cylinders, in the inter-row, at a depth of $2-7\,\mathrm{cm}$. Soil was sampled in an area of $1\,\mathrm{m}^2$ that was sprayed three weeks earlier with about $32\,\mathrm{ml}$ of $10\,\mathrm{g\,l}^{-1}$ glyphosate, in order to stop plant growth and therefore standardise sampling conditions between plots at the time of sampling. Soils were carefully transported within the cylinders to the laboratory where they were unmoulded. ~~Five~~ For each plot, five samples were air-dried until constant weight ~~during~~ for a period of about three months for QST analysis, whereas the last sample was dried at $105°\mathrm{C}$ and ~~weighted~~ weighed for the determination of bulk density. Additionally to structured soil samples, about $2\,\mathrm{kg}$ of each soil was sampled at the same location and depth and gently crumbled by hand for the measurement of soil ~~structural~~ aggregate stability by the **?** method and analysis of physico-chemical soil properties.

2.3 Soil analysis

2.3.1 Physico-chemical properties of soils

After ~~homogeneization~~homogenisation, about $500\,\mathrm{g}$ of each disturbed soil sample were gently crushed with a pie roll and sieved to $2\,\mathrm{mm}$, and the fraction $< 2\,\mathrm{mm}$ was sent to the *Centre interprovincial de l'agriculture et de la ruralité* in La Hulpe (Belgium) to be analysed. Soil pH was measured in water ($\mathrm{pH_{H_2O}}$) with a 1:5 soil:solution mass ratio, according to the norm NF-ISO-10390:2005 (**?**). Total C content was determined by dry combustion according to the norm NF-ISO-10694:1995 (**?**). Inorganic C content was measured by infrared quantification of $\mathrm{CO_2}$ emitted from soil after addition of orthophosphoric acid, according to the norm NF-EN-15936:2012 (**?**). SOC content was calculated as the difference between total and inorganic C content. ~~Granulometry analysis~~ Soil texture (sand, silt and clay contents) was ~~made~~ determined by sedimentation and sieving, according to Stokes law, by a method derived from the norm NF-X31-107:2003 (**?**). Bulk density was measured from one structured soil sample per plot, dried at $105°\mathrm{C}$ until constant weight, by dividing the mass of dry soil by the core volume ($100\,\mathrm{cm}^3$). The main properties of the soils of the experimental fields of the three trials are shown in ~~table 1~~the table 1 (open data available: https://doi.org/10.5281/zenodo.7405113).

2.3.2 Measurement of soil aggregate stability by *Le Bissonnais* method

Soil ~~structural~~ aggregate stability was measured according to the method of **?**, following the norm ISO-FDIS-10930:2011 (**?**). For each soil gently crumbled by hand, $5\,\mathrm{g}$ to $10\,\mathrm{g}$ of soil aggregates from 3 to $5\,\mathrm{mm}$ in size were subjected to three contrasting disaggregating treatments. The first test consists in ~~a~~ fast-wetting ~~of~~ soil aggregates in water, ~~to test their resistance to~~ exacerbating the effect of slaking. The second test is a slow-wetting of soil aggregates by capillarity, to test their resistance to clay dispersion and ~~swelling in wet conditions~~ differential swelling under wet conditions independently from the slaking effect. The third test consists in a standardised shaking of the aggregates in water after rewetting them in $95\,\%$ v/v ethanol for $30\,\mathrm{min}$, to test their mechanical strength ~~besides of the slakingeffect~~while minimising slaking, differential swelling and

Table 1. Soil properties of the 35 plots from the three long-term field trials. SOC = Soil Organic Carbon. The SOC:clay ratio was calculated for harmonised units for SOC and Clay, $\mathrm{g\,kg^{-1}}$. Open data available: https://doi.org/10.5281/zenodo.7405113

Plot	Treatment	Clay ~~Silt (fine~~($< 2\,\mu m$)	Silt (~~coarse~~2–50 μm)	~~Silt (total) Sand (fine~~Sand (50–2000 μm)	~~Sand (coarse) Sand (total)~~ SOC	SOC:clay	$\mathrm{pH_{H_2O}}$	Bulk density
		%	%	%	~~% % % %~~ $\mathrm{g\,kg^{-1}}$	[-]	[-]	$\mathrm{g\,cm^{-3}}$
Organic matter trial								
1	Farmyard manure	16.6	~~30.9 46.0~~ 76.9	~~5.3 1.2~~ 6.5	13.66	0.082	7.37	1.31
2	Farmyard manure	19.7	~~31.1 43.6~~ 74.7	~~4.5 1.1~~ 5.6	10.88	0.055	7.22	1.32
3	Farmyard manure	18.6	~~30.0 45.5~~ 75.5	~~4.9 1.0~~ 5.9	11.16	0.060	7.16	1.32
4	Residue exportation	16.1	~~29.2 48.4~~ 77.5	~~5.4 1.0~~ 6.4	8.82	0.055	7.07	1.28
5	Residue restitution	15.1	~~29.9 49.2~~ 79.1	~~4.7 1.1~~ 5.8	9.66	0.064	6.93	1.34
6	Residue restitution	14.8	~~30.7 48.1~~ 78.8	~~4.8 1.6~~ 6.4	9.84	0.067	6.86	1.30
7	Residue exportation	14.0	~~29.2 50.4~~ 79.6	~~5.2 1.2~~ 6.4	8.85	0.063	7.04	1.30
8	Farmyard manure	13.7	~~30.1 49.6~~ 79.7	~~5.2 1.4~~ 6.6	10.59	0.077	6.83	1.30
9	Residue exportation	15.8	~~29.3 48.8~~ 78.0	~~5.1 1.1~~ 6.2	8.80	0.056	6.88	1.34
10	Residue restitution	15.3	~~30.6 48.2~~ 78.8	~~4.7 1.2~~ 5.9	11.19	0.073	6.91	1.30
11	Residue restitution	18.9	~~31.0 44.6~~ 75.6	~~4.7 0.8~~ 5.6	9.84	0.052	6.99	1.32
12	Farmyard manure	15.3	~~29.9 48.6~~ 78.5	~~4.7 1.5~~ 6.2	10.22	0.067	6.75	1.36
13	Residue exportation	17.3	~~29.8 47.1~~ 76.9	~~4.6 1.2~~ 5.7	8.02	0.046	7.14	1.27
14	Farmyard manure	14.4	~~29.5 49.2~~ 78.8	~~5.4 1.4~~ 6.8	11.39	0.079	7.12	1.28
15	Residue restitution	17.1	~~30.1 46.8~~ 76.9	~~5.0 1.0~~ 6.0	9.81	0.057	6.98	1.30
16	Residue exportation	19.3	~~29.5 45.4~~ 74.9	~~4.9 0.9~~ 5.8	8.23	0.043	6.82	1.33

dispersion. After each disaggregation ~~treatments, the~~ treatment, the resulting aggregates were immersed in ethanol and dried at $40^{\circ}\mathrm{C}$ for 2 hours. The size distribution of the remaining aggregates was measured by way of dry sieving, with sieves of 2 mm, 1 mm, 0.5 mm, 0.2 mm, 0.1 mm and 0.05 mm.

Two main indicators were calculated from the fractions. The first is the mean ~~weighted~~ weight diameter (MWD) of the aggregate fraction that survived each individual test, following the equation (?):

$$MWD = \cancel{\frac{\sum(mean\ diameter\ between\ two\ sieves \times [weighted\ percentage\ of\ particles\ retained\ on\ the\ sieve])}{100}}\ \sum(mean\ diamete \tag{1}$$

The second indicator is the percentage of macro-aggregates (MA) remaining after each individual test, calculated as the mass fraction of soil aggregates $> 200\,\mu\mathrm{m}$.

The Le Bissonnais method has two main advantages ~~. First,~~ : (i) the three tests target the three main mechanisms of soil disaggregation in field conditions, namely slaking, ~~raindrop impact~~ mechanical breakdown and clay dispersion ~~; and second,~~ and (ii) it measures the size distribution of particles remaining after the disaggregation treatment, which provides further insight in soil susceptibility to water erosion (?).

2.3.3 Soil structural stability measurement by the ~~QuantiSlake Test~~ QuantiSlakeTest (QST) method

Whereas Le Bissonnais (1996) and other reference methods measure the stability of soil aggregates of a few mm in size, the QST works on 100 cm³ soil volumes rather than on soil aggregates. Accordingly, we consider that referring to 'soil structural stability' rather than 'soil aggregate stability' is more correct when referring to QST measurements, and we will therefore stick to "soil structural stability" for QST measures.

The QST method consists in ~~introducing a structured~~ plunging an undisturbed soil sample supported by ~~a~~ an 8 mm metallic mesh basket into ~~distilled~~ demineralised water, and measuring soil mass continuously ~~by dynamically weighting the content of the basket~~ using the underfloor ~~weighting~~ weighing hook of the balance. The balance is connected to a computer for ~~datalogging~~ data logging (Fig. 1). For each plot, the five air-dried structured soil samples were ~~slaked during~~ left to slake for approximately 1000 sec (around 17 min), with ~~a recording time frequency decreasing over time under water,~~ recording frequency decreasing from less than one second at the start of the experiment to approximately 30 s at the end. Due to some electronic or computer issues during the experiment, some samples were lost. ~~At the end~~In total, the data from 157 QST curves could be processed and constituted the main ~~data base~~ database of our study. Most of the 35 plots ~~gave~~ had five or four usable QST curves (20 and 13 plots respectively). One plot from the OM trial and one from the P-K mineral fertiliser trial ~~gave~~ had only three and two usable curves, respectively.

Immediately after soil immersion in water, the soil mass drops due to Archimedes' upward buoyant force ~~. This~~ (Fig. 2). The general shape of one QST curve is presented in Fig. 3, as well as main indicators that have been calculated from the curves. The first value of soil mass under water ~~(right after Archimedes' buoyancy)~~ is defined as the time 0 (t_0) of the QST ~~test. Then soil~~

~~mass~~ approach (Fig. 3). In the initial phase, soil mass generally increases due to ~~the release of air and the infilling of soil porosity by water~~ water filling porosity. After a few seconds or minutes, the ~~mass of cropland soils~~ soil mass reaches a maximum (W_{max} at t_{max}) before decreasing, once mass loss due to disaggregation becomes dominant compared to mass gain by wetting. Soil mass was normalised according to ~~the maximum mass value reached by each individual sample~~W_{max} ($W\,max = 1[-]$), so that mass values ~~vary~~ are relative soil masses, varying between 0 and 1. ~~Several indicators were~~

QST indicators calculated from the QST curves ~~(Fig. 3). QST indicators~~ were split into four categories (Fig.3) :

- (i) indicators related to the early increase in soil mass soon after soil immersion in water; they include the time to reach the maximum mass value (t_{max}); the increase in soil mass between t_0 and t_{max} (W_{max}-W_{t0}); and the slope between t_0 and t_{max} (Slope~~$_{t0\text{-}max}$~~$_{0\text{-}max}$);

- (ii) indicators related to ~~the early to intermediate mass loss after reaching the maximum mass; they consists in slopes~~ slopes in the decreasing part of the curve, at different timesteps (after 30 s, 60 s, 300 s and 600 s) in the decreasing part of the curve, taking t_{max} as the starting point (Slope$_{max\text{-}30}$, Slope$_{max\text{-}60}$, Slope$_{max\text{-}300}$ and Slope$_{max\text{-}600}$). Local slopes were also calculated between 30 s and 60 s (Slope$_{30\text{-}60}$), between 60 s and 300 s (Slope$_{60\text{-}300}$) and between 300 s and 600 s (Slope$_{300\text{-}600}$);

- (iii) indicators ~~specific to the intermediate to late mass lossof soil~~linked to threshold values of mass loss. They correspond to the time needed to reach a certain fraction of ~~total~~ relative mass loss between the maximum and the final mass of soil at the end of the QST experiment. Threshold values of 25, 50, 75, 90 and 95 % of relative mass loss were calculated (t25, t50, t75, t90 and t95)~~; and~~. The time between two threshold values of mass loss were also calculated (dt$_{max\text{-}25}$, dt$_{25\text{-}50}$, dt$_{50\text{-}75}$, dt$_{75\text{-}90}$ and dt$_{90\text{-}95}$). *Nota bene* - t25=dt$_{max\text{-}25}$, dt$_{max\text{-}25}$ will be used in the following manuscript, tables and figures ;

- (iv) global indicators providing a complete overview of soil mass evolution all over the QST. They include ~~sample~~ relative soil mass at the end of the experiment (W_{end}) and the Area Under Curve (AUC). For these two indicators, a reference time of 900 s was considered;

~~Calculation of each QST indicator is illustrated in Fig. 3.~~

~~thick square light grey boxes thin round light grey boxes~~

2.3.4 Measurement of root biomass after slaking

For samples from the soil tillage trial, root biomass retained in the metallic basket were ~~weighted~~ weighed after running the QST by cleaning remaining soil with a water jet. The roots were dried carefully with a Tork paper~~and weighted~~, air-dried and weighed.

2.3.5 ~~Statistical~~ Data analysis

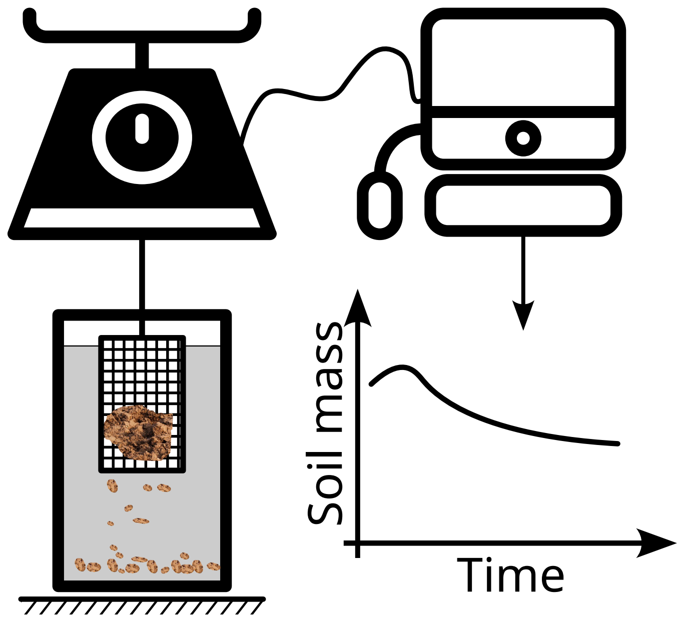

Figure 1. ~~Illustration of the QuantiSlake Test device, consisting~~ The QuantiSlakeTest (QST) aims in ~~the dynamic weighting of a structured~~ weighing an undisturbed soil sample suspended into ~~distilled~~ demineralised water by ~~a~~ means of an 8 mm mesh metallic basket. The QST device, illustrated here, consists in a balance ~~is~~ connected to a computer for direct datalogging. The ~~construction of an opensource user interface~~ open-source application for ~~managing QST laboratory~~ parameterising and driving the experience and for visualising data is ~~currently in progress~~released as a development R-package (<https://frdvnw.gitlab.io/slaker/dev/>). Video comparing the QST of two contrasting soil samples can be watched here: <https://youtu.be/G9UweThvHYI> – ~~Illustration~~ Credits : figure based on two ~~graphies~~ illustrations by Adnen Kadri from the Noun Project.

Between continuous variables, correlation coefficients were determined. For QST indicators, average values were calculated at the plot level for comparison with data that were measured only at the plot level: aggregate stability indicators from Le Bissonnais and physico-chemical soil properties. Since many QST indicators are calculated from one curve, a correlation matrix was drawn for QST indicators, to evaluate the level of redundancy between them and propose a selection to be used for the statistical analysis of soil management practices in the long-term experiments.

In order to test ~~if~~ whether soil management practices affect QST indicators, Linear Mixed-Effects Models were fitted and tested by analysis of variance (ANOVA). For each test, the QST indicator was used as the outcome variable and the treatments of the ~~trial~~ trials were used as a fixed explanatory variable, whereas the blocks were defined as a random effect. As several samples were related to one single plot (157 QST in total from 35 plots), the plot identifier was added as a random effect of the model to take into account the dependence between field ~~repetitions~~ replicates from one plot.

Prior to the ANOVA, the normality and the homoscedasticity of the residuals of the models were verified using respectively Shapiro-Wilk and Bartlett tests. For all the models, the significance of differences ~~of~~ in QST indicators between soil manage-

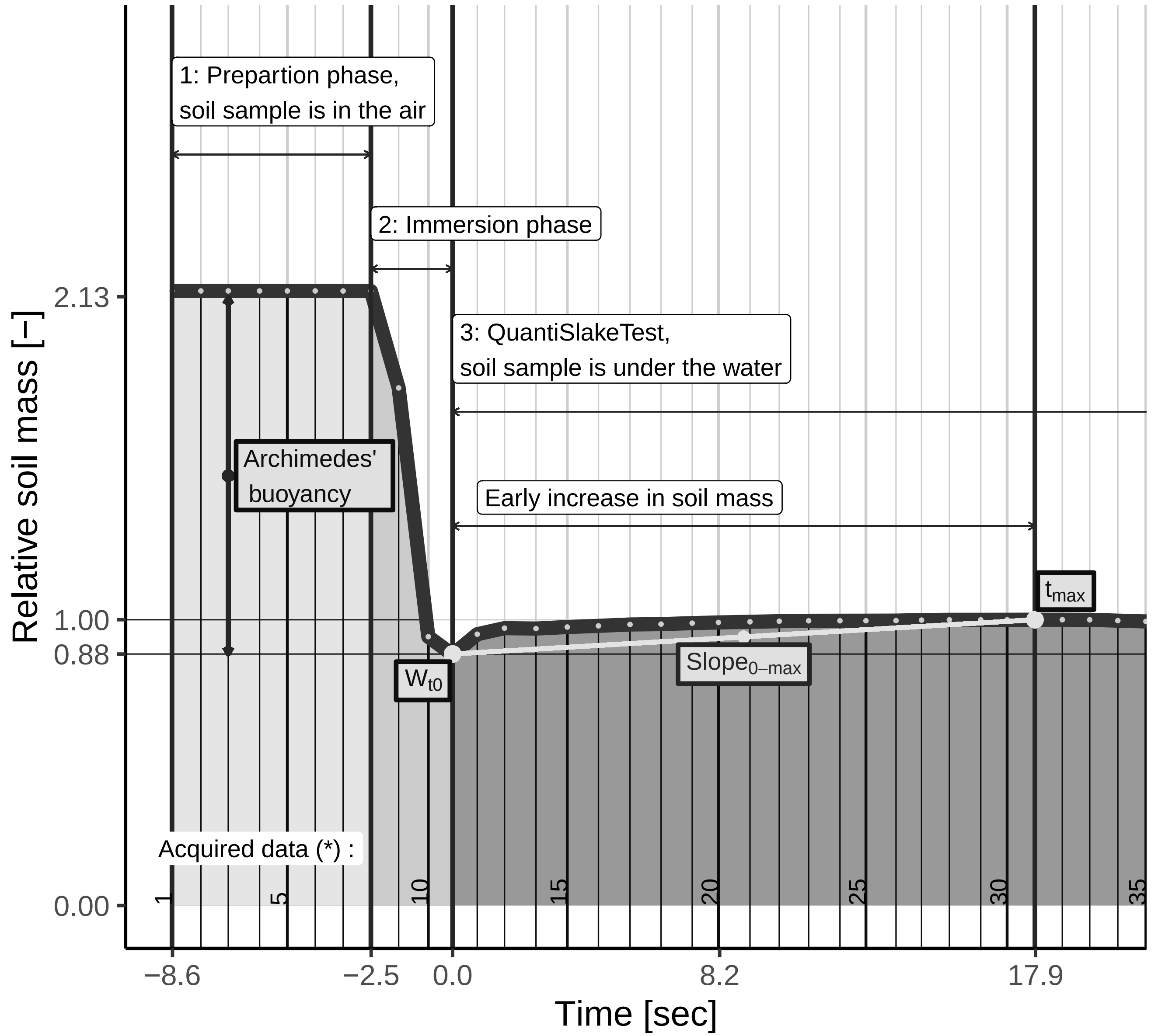

Figure 2. ~~Illustration~~ Early phases of ~~main QST parameters calculation from a curve (slake test on a soil sample from~~ the ~~plot 29~~QST, ~~P-K mineral fertiliser trial, see table 1). (i) Inside thick square light grey boxes (upper left), indicators related to~~ before and during the ~~early increase in soil mass including time to reach~~ immersion of the ~~maximum mass value (t_{max}); the increase in~~ soil ~~mass~~ sample. The Archimedes' buoyancy appears clearly between ~~t_0 and t_{max} (W_{max}-W_{t0}); and~~ the ~~slope between t_0 and t_{max}~~ first phase (~~$Slope_{t0\text{-}max}$~~preparation of the QST) ~~.~~ ~~(ii) In thick round white boxes (upper right), slopes at different timesteps (after 60 s, 300 s~~ and ~~600 s) in~~ the ~~decreasing part~~ beginning of the ~~curve, taking t_{max} as the starting point~~ third phase (~~$Slope_{max\text{-}60}$, $Slope_{max\text{-}300}$ and $Slope_{max\text{-}600}$~~the QST in itself). ~~For~~ Mathematical functions are used for automatically identified the ~~sake~~ starting of ~~clarity,~~ the ~~value of $Slope_{max\text{-}30}$ is not shown in the figure. (iii) In thin round white boxes (below the curve)~~test, ~~threshold values of 25, 50, 75, 90,95~~ based on first-order and ~~99% of mass loss (t25, t50, t75, t90, t95 and t99)~~second-order derivatives. ~~And finally, (iv)~~ The early increase in ~~black boxes, the two global indicators including sample~~ soil mass is only slightly visible at ~~the end of the experiment~~ this scale. (~~W_{end}~~*) Each vertical line represents one pair of data (time and weight) acquired by the ~~Area Under Curve (AUC~~computer, ~~shaded area)~~i.e. one line of the raw data file.

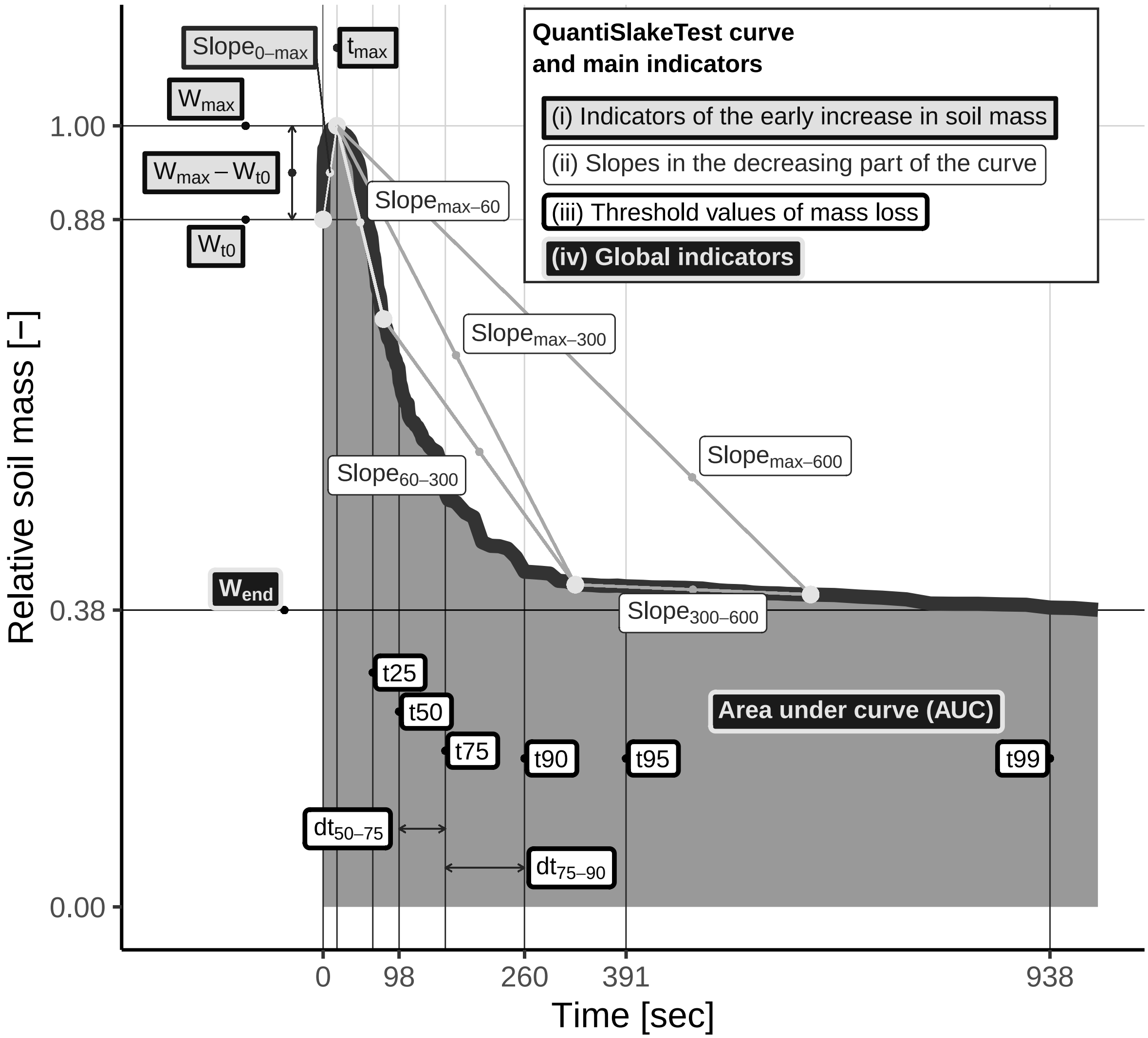

Figure 3. Main parameters are derived from a QST curve. (i) Inside thick square light grey boxes (upper left), indicators related to the early increase in soil mass including time to reach the maximum mass value (t_{max}); the increase in soil mass between t_0 and t_{max} (W_{max}-W_{t0}); and the slope between t_0 and t_{max} ($Slope_{t0\text{-}max}$). (ii) In thin round white boxes (upper right), slopes at different time steps (after 60 s, 300 s and 600 s) in the decreasing part of the curve, taking t_{max} as the starting point ($Slope_{max\text{-}60}$, $Slope_{max\text{-}300}$ and $Slope_{max\text{-}600}$) or between these time steps ($Slope_{60\text{-}300}$ and $Slope_{300\text{-}600}$). (iii) In thick round white boxes (below the curve), time needed to achieve 25, 50, 75, 90,95 and 99% of relative mass loss (t25, t50, t75, t90, t95 and t99) and between thresholds ($dt_{50\text{-}75}$ and $dt_{75\text{-}90}$). And finally, (iv) in black boxes, the two global indicators including sample relative mass at the end of the experiment (W_{end}) and the Area Under Curve (AUC, shaded area). For the sake of clarity, not all calculated indicators are shown here. For this illustration, the data from a real QST done on a sample from plot 29 of the P-K mineral fertiliser trial (see table 1)

ment practices were tested using classical analysis of variance (ANOVA, Type II Wald F tests with Kenward-Roger estimation of degree of freedom, **?**). When the F-test was significant (~~$p < 0.1$~~$p < 0.05$), post-hoc comparisons were performed: treatments of the trial were compared pairwise at 0.05 probability level of significance using estimated marginal means (EMMs, also named least-squares means, **?**).

~~Between continuous variables, correlation coefficients were determined. For QST indicators, average values were calculated at the plot level for comparison with other data (structural stability indicators from Le Bissonnais, physico-chemical properties) that were measured only at the plot level.~~

All statistical analyses were performed using ~~R-4.2.1 software (**?**)~~R version 4.3.0 (2023-04-21) software (**?**). The linear mixed-effect models were performed with the lme4 package (**?**), the ANOVA with the car package (**?**) and contrast analyses with the emmeans package (**?**).

3 Results

3.1 Redundancy analysis

The correlation matrix of QST indicators is presented in Appendix, in table A2. From this table, it appears that several indicators are strongly positively correlated. A high level of redundancy ($r > 0.9$) exists between:

- W_{end}, AUC, $Slope_{max\text{-}300}$ and $Slope_{max\text{-}600}$
- $Slope_{max\text{-}30}$ and $Slope_{max\text{-}60}$
- t_{max}, $dt_{max\text{-}25}$ and t50
- t50 and t75, t75 and t90, t90 and t95
- various dt and t (e.g.: $dt_{25\text{-}50}$ and t50, $dt_{50\text{-}75}$ and t75)

Accordingly, to limit redundancy, the output of the statistical analysis of QST indicators against soil management practices was limited to four QST indicators selected according to the following criteria: - One indicator was chosen for each category previously defined in the methods (i - early increase in soil mass; ii - early to intermediate mass loss; iii – intermediate to late mass loss; and iv - global indicators) - The use of highly redundant indicators ($r > 0.7$) was avoided. - In the same category of indicator, most discriminant indicators between soil management practices was chosen. If arbitration between two was necessary, the conceptually simplest one was kept.

According to these decision rules, we focused on (i) t_{max}, (ii) $Slope_{30\text{-}60}$ (for the tillage & PK trial) or $Slope_{60\text{-}300}$ (for the SOM trial), (iii) $dt_{50\text{-}75}$ and (iv) W_{end}.

3.2 Comparison of QST indicators with Le Bissonnais

Except for the Slope~~$_{t0\text{-}max}$~~$_{0\text{-}max}$, a positive correlation was found between all QST indicators and the mean weight diameter (MWD1) and the percentage of macro-aggregates (MA1) of the fast wetting test of Le Bissonnais (~~Fig.~~ Table 2). The higher correlation coefficients were found for QST indicators related to the early ~~stage~~ stages of the curve ~~, namely~~ (t_{max}, W_{max}-W_{t0}, Slope$_{max-30}$, Slope$_{max-60}$, ~~t25~~ dt$_{max-25}$ and t50). Correlation decreases progressively for later slopes (Slope$_{max-300}$, Slope$_{max-600}$) as well as for t75 to t95 and is minimal for sample residual mass at the end of the test (W$_{end}$). Similarly, the mean weight diameters (MWD2) of the slow wetting test of Le Bissonnais also correlate positively with each QST indicator except Slope~~0-max~~$_{0-max}$. However, ~~correlation~~ correlations tend to increase for QST indicators related to the intermediate to late stage of the curve, particularly t50 to t95 ~~(Fig.~~ and dt$_{max-25}$, dt$_{25-50}$ and dt$_{50-75}$ (Table 2). In contrast to the fast wetting test, the percentage of macro-aggregates surviving the slow wetting (MA2) are poorly related to QST indicators. For the third test of Le Bissonnais, testing soil ~~mechanical strength~~resistance to mechanical breakdown, mean weight diameter (MWD3) correlates poorly with QST indicators. Similarly, correlation between QST indicators and the percentage of macro-aggregates surviving the third test (MA3) is always negative and generally poor, except for W$_{max}$-W$_{t0}$ (r=-0.60, ~~Fig.~~ Table 2). Regardless of the test, sample mass at the end of the experiment (W$_{end}$) ~~correlate~~ correlates poorly with MWDs from Le Bissonnais, considered alone or in combination (data not shown). Correlation between the area under curve (AUC) and MWD1 (r=~~0.42~~0.41) and MWD2 (r=0.38) ~~and the area under curve (AUC)~~ is a bit higher but remains poor.

3.3 Soil aggregate and structural stability against soil properties

3.3.1 Le Bissonnais

The correlation matrix between Le Bissonnais' indicators and soil properties is shown in Appendix, in table A1. A positive correlation exists between total SOC content and both MWD1 (r=0.75) and MWD2 (r=0.70), whereas MWD3 and MA3 correlate poorly with SOC content (r=0.11 and -0.07, respectively). In contrast, clay content correlates positively with MWD3 and MA3 (r=0.52 and 0.66, respectively) but poorly with MWD1 and MWD2 (r=-0.35 and -0.12). Linear relationship with the SOC:clay ratio, evidenced as a proxy for predicting field soil structural ~~stability~~ quality by visual assessment methods (**?**) was also tested. The SOC:clay ratio correlated positively with both MWD1 (r=0.67) and MWD2 (r=0.48) and negatively with MWD3 (r=-0.33) and MA3 (r=-0.55). No clear linear relationship was found between Le Bissonnais' ~~s~~ indicators and pH or bulk density.

3.3.2 ~~QuantiSlake test~~QuantiSlakeTest

~~Except for the Slope$_{0-max}$~~Generally, indicators derived from QST curves correlate ~~all~~ positively with SOC content, except for Slope$_{0-max}$ and Slope$_{60-300}$ and Slope$_{300-600}$. Coefficients remain low to moderate though, with the stronger coefficient obtained for W$_{max}$-W$_{t0}$ (r=0.56) and t95 (r=0.55) (~~Fig.~~ Table 2). In contrast, ~~all~~ most QST indicators correlate negatively with clay content. The stronger coefficients were found for W$_{max}$-W$_{t0}$ (r=-0.83), t$_{max}$ (r=~~-0.68~~-0.67), Slope$_{max-30}$ (r=-0.64) and AUC (r=~~-0.59) (Fig.~~ -0.58) (Table 2). This ~~seemingly~~ antagonist effect of SOC and clay contents on soil resistance to disaggregation under water is well captured by the SOC:clay ratio, which correlates strongly with indicators from the start of QST curves, particularly W$_{max}$-W$_{t0}$ (r=~~0.925, Fig.~~ 0.92, Table 2 and detailed in Fig. 4) but also t$_{max}$ (r=0.82), Slope$_{max-30}$ (r=0.67) ~~, Slope~~and dt~~max-60~~$_{max-25}$ (r=~~0.69)and t25 (r=0.68).~~ 0.68). While we observe a clear relationships between W$_{max}$-W$_{t0}$ and SOC:clay ratio

Table 2. Correlation coefficients between ~~average~~ QST indicators calculated from individual curves, Mean Weight Diameters (MWD) and percentages of macro-aggregates (MA) from the three tests of Le Bissonnais (1. Fast wetting; 2. Slow wetting; 3. ~~Shaking in water after rewetting with EtOH~~Mechanical breakdown) and soil properties. The gradient of colours relates to the positive (~~blues~~blue) or to the negative (~~oranges~~orange) relative amplitude of correlation coefficients.

	Le Bissonnais *et al.* (1996)						Soil properties				
	MWD 1	MWD 2	MWD 3	MA 1	MA 2	MA 3	SOC	Clay	SOC:Clay	pH	Bulk density
(i) QST indicators of the early increase in soil mass											
Slope 0-max	-0.12	-0.15	0.09	-0.19	0.06	0.32	-0.03	0.39	-0.34	-0.08	0.09
tmax	0.60	0.51	-0.26	0.57	-0.06	-0.46	0.52	-0.67	0.82	0.03	-0.49
Wmax-Wt0	0.58	0.36	-0.37	0.57	-0.12	-0.60	0.56	-0.83	0.92	0.08	-0.61
(ii) QST slopes in the decreasing part of the curve											
Slope max-30	0.47	0.37	-0.16	0.48	0.02	-0.36	0.41	-0.64	0.67	-0.03	-0.14
Slope 30-60	0.48	0.50	0.11	0.38	0.09	-0.09	0.38	-0.33	0.49	-0.20	-0.28
Slope 60-300	-0.10	-0.04	0.17	-0.20	-0.27	-0.02	-0.18	-0.11	0.02	0.19	-0.42
Slope 300-600	-0.33	-0.45	-0.04	-0.29	-0.23	0.00	-0.37	0.07	-0.25	0.09	-0.13
(iii) QST threshold values of mass loss											
dt max-25	0.60	0.50	-0.18	0.57	0.04	-0.32	0.52	-0.51	0.68	-0.08	-0.18
dt 25-50	0.49	0.57	-0.07	0.41	0.10	-0.21	0.43	-0.29	0.52	-0.01	-0.23
dt 50-75	0.38	0.68	-0.01	0.32	0.20	-0.14	0.47	-0.23	0.49	0.05	-0.32
dt 75-90	0.25	0.36	-0.08	0.23	0.14	-0.24	0.32	-0.27	0.44	0.09	-0.26
t50	0.57	0.56	-0.13	0.52	0.07	-0.28	0.50	-0.43	0.63	-0.05	-0.21
t75	0.49	0.66	-0.06	0.43	0.15	-0.21	0.51	-0.33	0.58	0.01	-0.29
t90	0.43	0.59	-0.08	0.38	0.16	-0.25	0.48	-0.34	0.58	0.05	-0.31
t95	0.39	0.64	-0.09	0.36	0.22	-0.27	0.55	-0.35	0.61	0.15	-0.34
(iv) QST global indicators											
Wend	0.33	0.27	0.03	0.26	-0.17	-0.25	0.20	-0.54	0.53	0.00	-0.39
AUC	0.41	0.38	0.01	0.35	-0.10	-0.28	0.30	-0.58	0.61	-0.01	-0.38

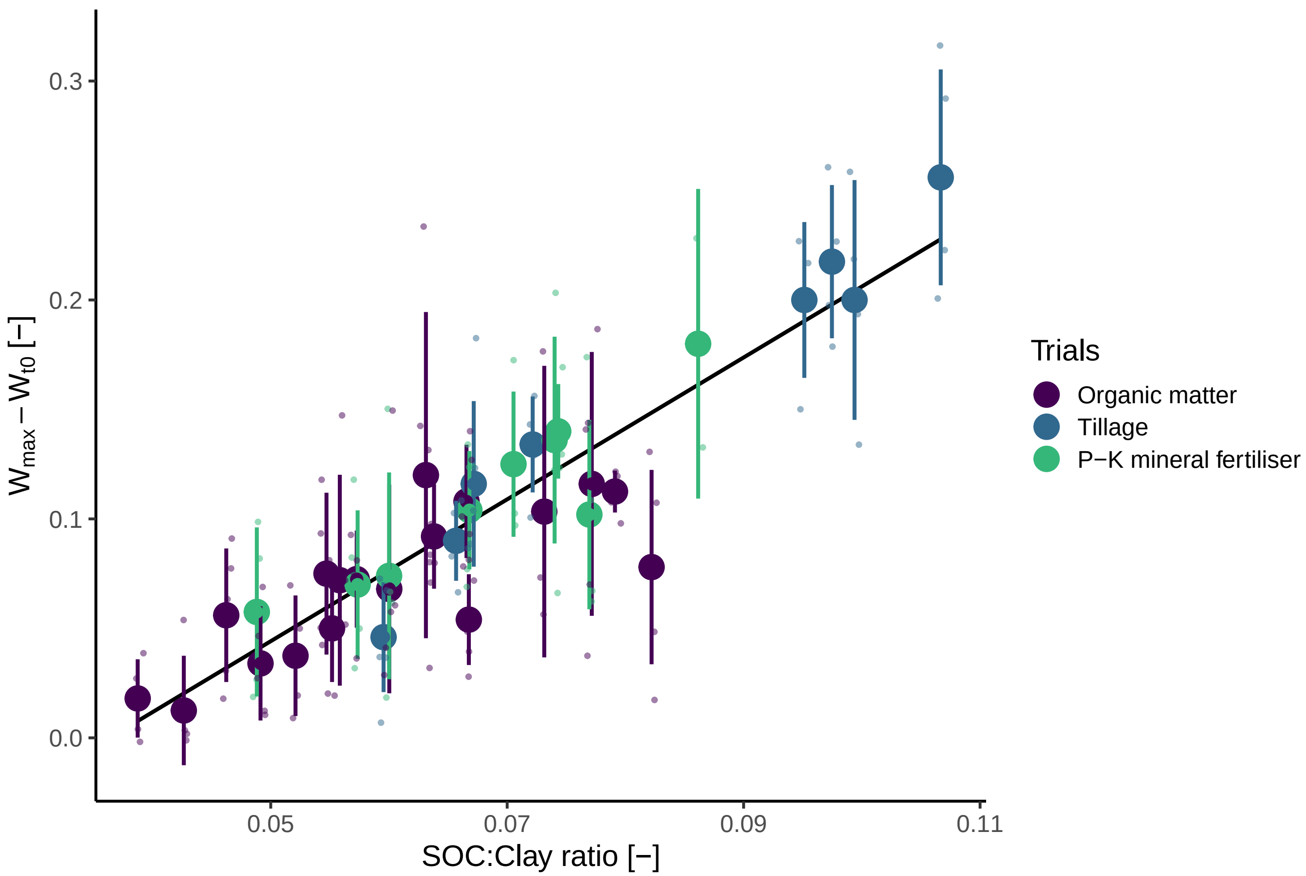

Figure 4. Early increase in soil mass under water measured from QST curves (W_{max}-W_{t0}) against the SOC:clay ratio of bulk soil (r=~~0.925~~0.92). Small dots are individual QST indicator with a small amount of noise added in x. Large dots are the mean ~~(M)~~ and bars are standard deviation ~~(sd)~~ by plot~~(M-sd, M+sd)~~.

(Fig. 4, we observe a residual variability in the repeated test of a same plot, that could be explained by local soil conditions of the sampling sites (eg. slopes, presence of roots, or earthworms' galleries).

Similarly to indicators of soil ~~structural~~ aggregate stability from Le Bissonnais, all indicators from the QST curves correlated poorly with pH. Except for $Slope_{0\text{-}max}$, a moderate to poor negative correlation is observed between QST indicators and bulk density, with the lower values obtained for W_{max}-W_{t0} (r=-0.61) and t_{max} (r=-0.49).

3.4 Soil structural stability under contrasting ~~agricultural~~ soil management practices

The responses of soil structural stability indicators calculated from QST curves to contrasting long-term soil management practices from the three ~~field trials~~ long-term experiments are presented in this section. For the sake of clarity ~~, we put the focus~~ and to limit redundancy, we have focused on a selection of ~~nine indicatorsrepresentative for~~ four indicators: (i) ~~the start of the~~

~~curve (W_{max}-W_0,~~ t_{max}, ~~Slope~~(ii) $Slope_{~~max-30~~30\text{-}60}$ ~~, Slope~~for the tillage & PK trial or $Slope_{~~max-60), (ii) intermediate and late stages~~ 60\text{-}300}$ for the SOM trial, (iii) $dt_{50\text{-}75}$ and (iv) W_{end}, one for each category defined in the methods: (i) early increase in soil mass, (ii) slopes in the decreasing part of the curve~~($Slope_{max-300}$, t75~~, ~~t95) and (iii) global QST indicators(W_{end}, AUC)~~(iii) threshold values of mass loss and (iv) global indicators.

3.4.1 Organic matter trial

Soils of the three treatments of OM inputs in the OM trial have different contents of total SOC, with the FYM treatment having the highest SOC content ($11.32\,\mathrm{g\,kg^{-1}}$), the RE treatment having the lowest SOC content ($8.41\,\mathrm{g\,kg^{-1}}$) and the RR treatment having ~~intermediate values~~ an intermediate value ($9.95\,\mathrm{g\,kg^{-1}}$). ~~QST indicators from the start of the QST curves (W_{max}-W_{t0}~~Accordingly, t_{max} ~~, $Slope_{max-30}$) tend~~ tends to respect this gradient of total SOC, with the FYM ~~and RR treatments showing better~~ showing the best scores on average ~~than the RE treatment, even if differences are small and only significant ($p < 0.1$) for t_{max}~~ ($p = 0.047$, Fig. 5a-d). Counter-intuitively though, this order is not respected anymore for ~~other~~ QST indicators related to intermediate or late stages of the curves ($Slope_{60\text{-}300}$, W_{end}). The response of treatments follows the order RR > ~~FYM > RE for Slope~~RE > FYM for $Slope_{~~max-60~~60\text{-}300}$ (~~n.s.~~$p = 0.005$, Fig. 5~~d) and $Slope_{max-300}$ ($p < 0.1$, Fig. 5e), and FYM shows an average score even lower than RE (n.s.) and significantly lower than RR~~ c) and for W_{end} (~~$p < 0.1$~~$p = 0.098$, Fig. 5~~h). Conflicting~~ d). Discordant results were also obtained between the three tests of Le Bissonnais, with the MWD scores from the fast wetting test (MWD1) ~~and from the shaking (MWD3) in favor~~ slightly in favour of the FYM treatment (FYM ~ RR > RE~~) but~~; n.s., results in Appendix, Fig. **??**) the scores from the slow wetting test ~~in favor~~ (MWD2, n.s.) and from the mechanical breakdown (MWD3, $p < 0.05$) in favour of the RR treatment (RR > FYM ~ RE; results in Appendix, Fig. **??**).

3.4.2 Tillage trial

Remarkably, the QST responds very well to contrasting tillage treatments, with all QST indicators having a better score for reduced tillage (RT) than for ploughing (P) (Fig. 6 and Fig. 7). This result is in agreement with total SOC content, RT having an average SOC content of $12.16\,\mathrm{g\,kg^{-1}}$ whereas P treatments have an average SOC content of $10.07\,\mathrm{g\,kg^{-1}}$. ~~However, $Slope_{max-60}$, $Slope_{max-300}$, $Slope_{max-600}$ (respectively $p < 0.05$, $p < 0.01$, $p < 0.01$) and global QST indicators (W_{end}, AUC, respectively, $p < 0.01$ and $p < 0.05$, Fig. 7d-e,h-i) tend to discriminate better between tillage treatments than indicators from the start of the curve (W_{max}-W_{t0},~~ Similarly, a higher root biomass content was measured in the topsoil under RT, with $42 \pm 19\,\mathrm{mg}$ of root biomass for the RT treatment against $31 \pm 16\,\mathrm{mg}$ for the P treatment (p=0.168). However, Slope~30-60 ($p < 0.007$) and W_{end} ($p < 0.008$) are more sensitive to tillage than t_{max} and ~~Slope~~$dt_{~~max-30~~50\text{-}75}$ ~~, respectively $p < 0.1$, n.s. and n.s.,~~ (Fig. 7~~a-e~~). Indicators from the three tests of Le Bissonnais provide similar results, with the most contrasting response between RT and P tillage treatments obtained for the fast wetting test ~~.~~ (Appendix, Fig. **??**). However, $Slope_{~~max-300~~30\text{-}60}$ ~~, $Slope_{max-600}$~~ and W_{end} discriminate better between tillage treatments than MWD1 ($p < 0.05$).

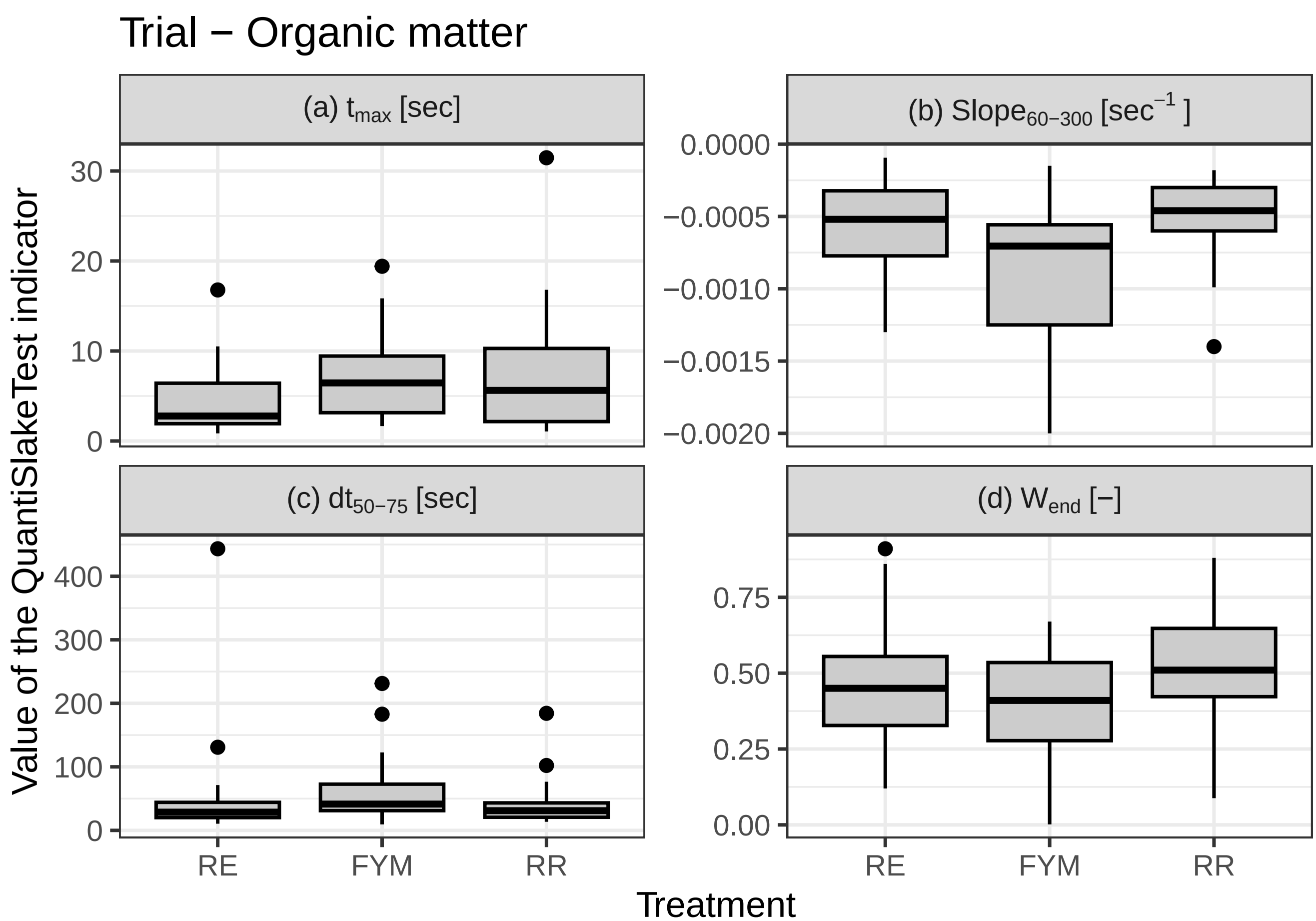

Figure 5. Boxplots of ~~nine~~ four QST indicators against treatments of OM input for the soils from the organic matter trial, 'residue exportation' (RE), 'farmyard manure' (FYM) and 'residue restitution' (RR). a) ~~W~~t_{max}~~$-W_{t0}$~~; b) ~~t_{max}~~$Slope_{60\text{-}300}$; c) ~~$Slope_{max\text{-}30}$~~$dt_{50\text{-}75}$; d) ~~$Slope_{max\text{-}60}$; e) $Slope_{max\text{-}300}$; f) t75; g) t95; h)~~ W_{end}~~; i) AUC~~.

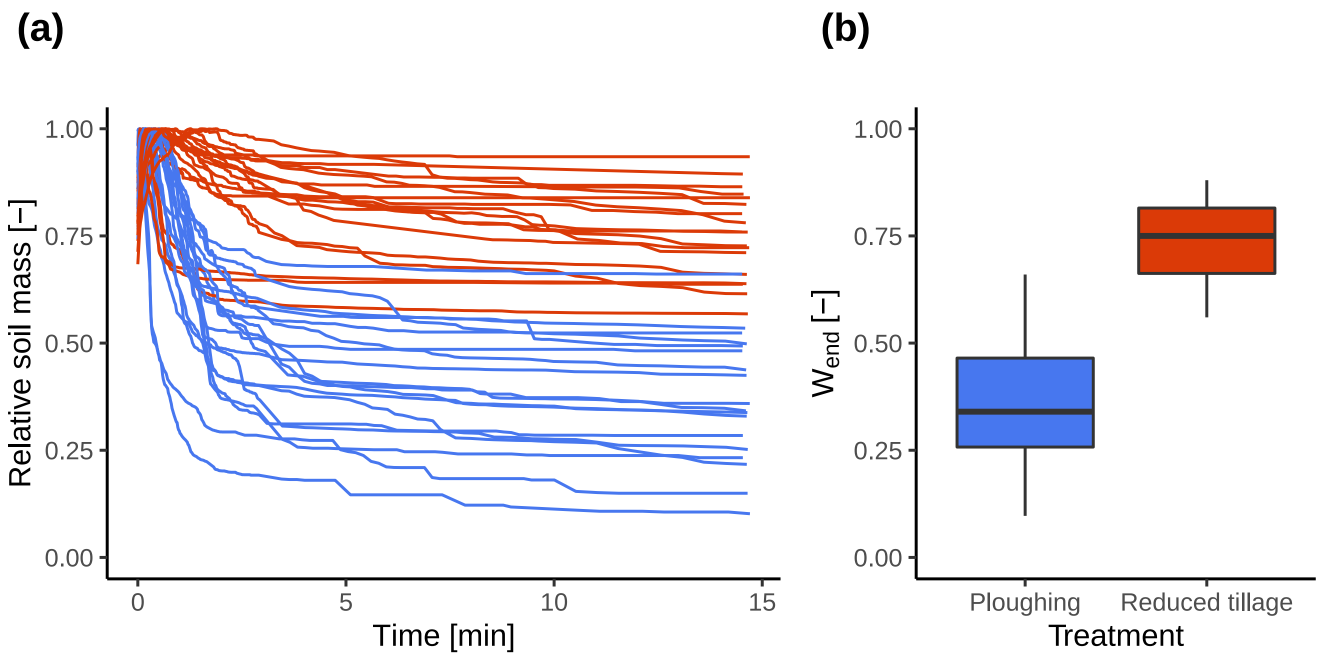

Figure 6. QST curves (a) and final relative mass (W_{end}, b) for ploughing and reduced tillage treatments of the tillage trial.

3.4.3 P-K mineral fertiliser trial

In the P-K mineral fertiliser trial, soil structural stability respects the order K2 > K0 > K1 regardless of the QST indicator (data not shown), but without any significant differences (n.s.). Similar results were obtained with the three tests of Le Bissonnais but with a smaller standard deviation on average than that ~~for~~ of QST indicators.

4 Discussion

4.1 Interpretation of QST curves in light of mechanisms of soil disaggregation and soil properties

4.1.1 Mechanisms of soil disaggregation

Right after immersion in water, soil mass increases due to the replacement of air by water in soil porosity. Sooner or later, soil mass then reaches a maximum before decreasing when mass loss by disaggregation exceeds mass gain due to ~~infilling~~ filling of soil porosity with water. QST indicators from the start of the curves (e. g. W_{max}-$W_{\cancel{\theta}t0}$, t_{max}, $Slope_{max-30}$~~, $Slope_{max-60}$, t25~~) are the most correlated to the fast wetting test of Le Bissonnais (MWD1 and MA1; ~~Fig.~~ Table 2), which indicates that ~~the early mass loss under water is mainly controlled by slaking~~ slaking significantly contributes to the initial stage of the QST. In contrast, QST indicators from the intermediate to late stages of the curves (~~t50~~ e. g. t75 to t95) are more correlated to the

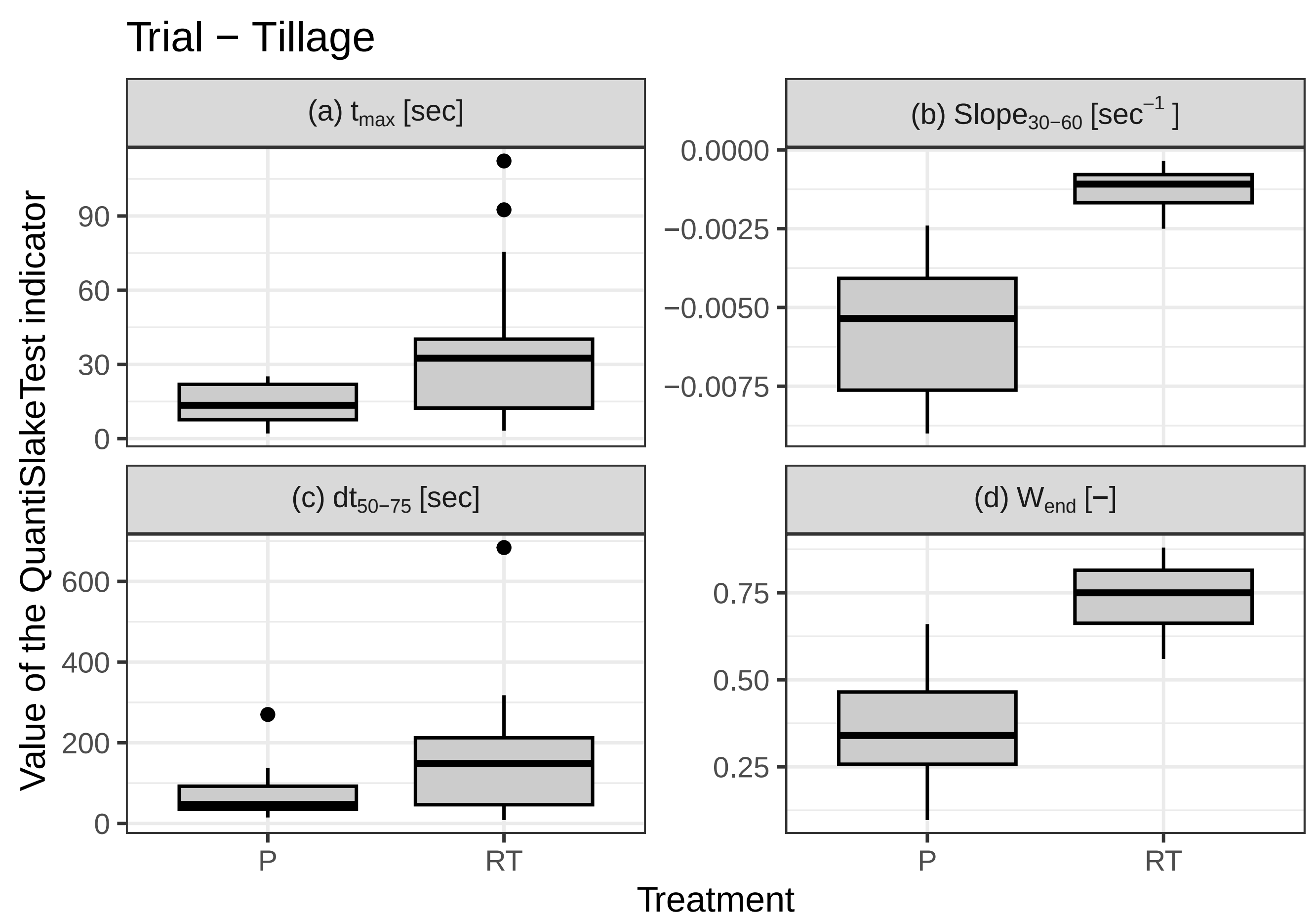

Figure 7. Boxplots of ~~nine~~ four QST indicators against tillage treatments, ploughing (P) and reduced tillage (RT) for the soils from the tillage trial. a) ~~W~~t_{max} ~~-W_{t0}~~; b) ~~t_{max}~~ $Slope_{30\text{-}60}$; c) ~~$Slope_{max\text{-}30}$~~ $dt_{50\text{-}75}$; d) ~~$Slope_{max\text{-}60}$; e) $Slope_{max\text{-}300}$; f) t75; g) t95; h)~~ W_{end} ~~; i) AUC~~.

slow-wetting test of Le Bissonnais (~~Fig.~~ Table 2), specifically targeting clay dispersion and differential swelling. This indicates that after a longer time period under water, when soil is saturated, the effect of slaking decreases and clay dispersion ~~becomes the dominant mechanism~~ and differential swelling become the dominant mechanisms of soil disaggregation. Nevertheless, both mechanisms overlap, with air release from soil further interfering with the measurement of soil mass loss when running QST. This may explain ~~for~~ the relatively low correlation coefficients obtained between QST slopes and indicators from the fast and slow wetting tests of Le Bissonnais. ~~We also advocate that the fast-wetting test of Le Bissonnais is unable to measure the effect of slaking independently from the effect of clay dispersion, and rather provides a measurement of the effect of slaking and clay dispersion combined. Indeed, our results suggest that, for the silt loam soils low in SOC content of this study ,~~ It is also worth mentioning that the time of wetting of the ~~timing of 10 minutes under water recommended for the fast-wetting test of Le Bissonnais is too long to specifically target slaking, since air release from the sample lasted much less than 10 minutes.~~

~~Accordingly, the final mass (W_{end}) of the sample was often reached, or close to, after 10 minutes. Therefore, we think that some QST indicators might be~~ soils of our study was relatively short (less than two minutes, as indicated by the release of air bubbles from soil). We therefore advocate that indicators from the initial stage of the curve, like $Slope_{30-60}$, may provide information much more specific to slaking than ~~the fast-wetting~~ indicators from the fast wetting test of Le Bissonnais, ~~such as $Slope_{max-60}$~~ lasting ten minutes, which largely exceeds the time during which slaking is the dominant driver of disaggregation.

~~Excepted~~ Except for W_{max}-W_{t0}, QST indicators ~~are very poorly correlated~~ correlate very poorly to the third test of Le Bissonnais, targeting soil ~~resistance to raindrop impact~~ mechanical resistance (**?**). This indicates that little information on soil resistance to raindrop impact or shear strength from agricultural machinery can be inferred from QST curves, which is not surprising. For the soils of this study, soil ~~resistance to raindrop impact~~ mechanical resistance (as estimated by the third test of LeBissonnais) seems to be somehow controlled by the absolute clay content of soil, since clay content correlates positively to MWD3 (r=0.52) and MA3 (r=0.66).

4.1.2 The response of QST indicators to soil properties

Soil mass evolution under water as captured by QST indicators respond in an antagonist way to SOC and clay contents. Indeed, ~~all~~ most QST indicators are positively correlated to SOC content and negatively correlated to clay content, with the absolute value of correlation coefficients decreasing for indicators of the later part of the curves ($Slope_{\cancel{max-300}\,60-300}$, $Slope_{\cancel{max-600}\,300-600}$ and W_{end}). Similar trends were observed in other contexts, with the resistance to slaking increasing with SOC content and decreasing with clay content (**??**). In light of the comparison between QST curves and Le Bissonnais's indicators, the amplitude of the early mass loss under water is mainly controlled by soil resistance to slaking. Accordingly, the absolute SOC content increases soil resistance to slaking, as highlighted by the positive correlation between SOC content and ~~indicators derived from the fast wetting test of Le Bissonnais (~~MWD1 ~~, MA1~~(r=0.75) . The role of SOM in promoting soil ~~structural~~ aggregate stability is well-know (**??????**), as SOM has long been recognised as one of the main binding agent in micro-aggregates (**??**). The increase in SOC along a field gradient has been shown to decrease the wettability of individual aggregates from 3 to 5 mm in diameter and of SOM-associated clay in the $< 2\,\mu m$ fraction of soil (**?**). This decrease in clay wettability might explain, in part at least, the higher ~~structural~~ aggregate stability under water of soils rich in SOC, with the slower wettability of macro-aggregates explaining ~~for~~ their improved resistance to slaking (**?**) and the slower wettability of clay decreasing its dispersive character (**??**).

In contrast, while the absolute clay content increases soil ~~resistance to raindrop impact~~ mechanical resistance (supported by the positive correlation with MWD3 and MA3), it also tends to decrease soil structural stability under water (as indicated by the negative correlation with most QST indicators). This supports the view that, for cropland soils of this study ~~low in~~ with low SOC content on average, clay dispersivity and differential swelling are strong drivers of soil disaggregation in wet conditions. This is in agreement with the findings of **?** who found that, for soils from France and Poland, clay has a dispersive power in water that is reduced once complexed with SOM, with an average complexation potential of 1 g of SOM for 10 g of clay. This threshold value of 0.1 for mass SOC:clay ratio was reported as pivotal between good and medium structural quality as estimated by field visual soil assessment by the CoreVESS method for 161 agricultural soils of Switzerland (**?**) and for a large number of forest, grassland and cropland soils from England and Wales (**?**). Additionally, both **?** and **?** found a linear increase in soil structural ~~stability~~ quality scores with increasing SOC:clay ratios in the range $1:13$ to $1:8$, suggesting that SOM has beneficial effects on soil structure beyond the threshold value of $1:10$ determined empirically by **?**. We assume that ~~that~~ these results can be extrapolated to other temperate European soils under similar pedoclimatic conditions and clay mineralogy, as supported by the linear increase of QST indicator W_{max}-W_{t0} with the SOC:clay ratio in the range $0.04-0.12$ (Fig. 4). This supports the idea that W_{max}-W_{t0}, as a predictor of the SOC:clay ratio, has the potential to ~~evaluate~~ estimate the overall soil structural ~~stability~~ quality as measured in field conditions with visual soil assessment methods.

It is important to underline that the close linear relationship found between W_{max}-W_{t0} and the SOC:clay ratio (see Fig. 4) has probably no general character and was obtained here because cropland soils of the current study were sampled under standardised conditions of seeding and cover (winter wheat). It is very unlikely to find an identical relationship for the same soils under contrasting conditions of soil preparation, sampling dates or crop type, since soil ~~structural stability doesn't only relate to the SOC:clay ratio but also to~~ structure does also relate to more or less dynamic external factors such as tillage, root and hyphae development, biological activity, etc~~. . .~~ . To sum up, we suggest that the SOC:clay ratio must be seen as a proxy for soil intrinsic 'potential' structural stability, with the threshold value of 0.1 being a reasonable target for SOM management at field and farm scales (**???**). On the other hand, QST indicators such as W_{max}-W_{t0} ~~from QST curves provides~~ provide a quantitative, direct measurement of the overall structural stability of a soil under a given set of conditions. Both parameters are therefore relevant in terms of appreciation of soil resistance to water erosion and structural damage by farm machinery.

4.2 The response of QST indicators to agricultural practices

One challenge for the interpretation of QST curves is the choice of the most suitable indicator(s) to assess ~~overall~~ soil structural stability~~in a given context~~. For the tillage and P-K mineral fertiliser trials, the choice of one indicator rather than another is not critical because indicators from QST curves are consistent with each other and with indicators from Le Bissonnais. In contrast, for the treatments of the organic matter trial, results ~~are discordant~~ differ between indicators from the start and the end of the QST curves. This originates from curves having different shapes according to the treatments, suggesting differences in disaggregation mechanisms from one treatment to another. The FYM treatment resists ~~better to disaggregation~~ disaggregation more strongly at the start of the QST, whereas RR is the best treatment against disaggregation under water at the end of QST curves (Fig. 5). This last result is counter-intuitive, since the FYM treatment has a higher total SOC content than the RR treatment. Nevertheless, similar results had already been reported on the same trial (**?**), with the RR treatment resisting better than FYM to disaggregation by wet sieving. This result in conflict with total SOC content must be regarded in light of (i) the quality of SOM inputs and (ii) the frequency of SOM restitution. **?** calculated that the FYM and RR treatments receive on average similar amounts of C inputs, 472 ± 82 and $487\pm93\,\mathrm{gC\,m^{-2}\,y^{-1}}$, respectively. Over time, this amount of C input by farmyard manure application has led to an increase of total SOC content (about $12\,\mathrm{g\,kg^{-1}}$ for the FYM treatment) whereas for the RR treatment, an equivalent C input by green manure and residue restitution only allowed to maintain SOC content to the initial level ~~(about 10 g kg^{-1}; Buysse2013a)~~(about $10\,\mathrm{g\,kg^{-1}}$; **?**). A smaller SOC storage for a similar C input means a higher rate of mineralisation. The formation of water-stable aggregates under the effect of microbial decomposition of root biomass is a known process ~~(e.g., ?)~~(e.g, ?). In the present study, the more microbially active, labile biomass from green manure and crop residues seems to have had a stronger impact on the later part of the QST curve, controlled by clay dispersion and differential swelling, whereas the ~~more processed~~composted, stable biomass of the farmyard manure had more impact on soil resistance to slaking. This is in agreement with an important contribution of root and fungal ~~exsudates~~ exudates as well as microbial mucilages, known as critical binding agents in micro-aggregates (?), on the reduction of clay dispersivity. Dispersive clay has been proved an important driver of soil erodibility (??). In contrast, soil resistance to slaking appears to be more related to the total content of SOC, with slaking having little effect on micro-aggregates $< 250\,\mu m$ (?). Another important point is the frequency of SOM inputs, with the FYM treatment receiving cattle manure once every three years whereas the RR treatment receives an extra SOM input annually, in the form of green manure or chopped straw. The ~~FYM treatment might have obtained better soil structural stability scores if sampling had occurred shortly after FYM application (the~~ last FYM application occurred almost two years before the sampling campaign~~)~~.

For the tillage trial, reduced tillage (RT) improves soil structural stability regardless of the QST indicator (Fig. 7)~~, even though some late-stage and global indicators (Slope~~. However, indicators from the late part of QST curves (Slope$_{\cancel{max\text{-}300}\,60\text{-}300}$, Slope$_{\cancel{max\text{-}600}\,300\text{-}600}$~~,~~) and global indicators (W_{end} and AUC) tend to discriminate better between tillage treatments. This result is consistent with an increase in both total SOC content and root biomass in the $2-7$ cm topsoil~~(RT: 42 ± 19 mg of root biomass for 100 cm^3; P: 31 ± 16 mg of root biomass for 100 cm^3, p=0.168)~~.The gradient of concentration of SOC and nutrients from the surface soil under RT is a known effect once vertical dilution by ploughing is stopped (???). This higher nutrient content in the topsoil may explain ~~for~~ the higher root density. Whereas a higher root density is known to play a key role in soil macroaggregation, ~~a~~ higher root density and SOC ~~content~~ contents in the topsoil also advocate for a higher biological activity. This is in line with a better microaggregation and a better performance of indicators from the end of QST curves under RT, related to a better resistance to clay dispersion. ~~This is supported by the fact that the relationship between QST indicators and the amount of root biomass was relatively poor for QST indicators from the start of the curves (Fig. ??a-c) and increased for the later ones (Fig. ??d-f).~~ Overall, results from the OM and the tillage ~~trial~~ long-term experiment support the view that living and labile biomass plays an important role in decreasing clay dispersion. ~~This result is in agreement with the fact that labile biomass from green manure and crop residues has more effect than composted farmyard manure on the reduction of clay dispersion in the OM trial.~~

For the P-K mineral fertiliser trial, the working assumption that KCl application might decrease soil ~~structural stability due to the presence of destructuring chloride anions~~ aggregate stability (?) was not verified. This ~~is probably due to the fact that the~~ might be due to a relatively short-lived disaggregating effect of ~~is relatively short-lived after application of , with being lixiviated downwards over time with water fluxes. Since the last KCl~~ KCl, since the last application occurred in the summer of 2016, ~~the absence of residual disaggregating effect from anions is not surprising~~almost three years before soil sampling. The beneficial effect of K fertilisation on crop production and restitution of organic matter to soil might also have ~~further~~ counteracted a potentially negative short-term effect~~of~~.

~~Scatterplots for six indicators (W_{max}-W_{t0}, Slope$_{max\text{-}30}$, Slope$_{max\text{-}60}$, Slope$_{max\text{-}300}$, Slope$_{max\text{-}600}$, W_{end}) from various individual QST curves from the tillage trial against root biomass (mg) collected in the basket after running the QST.~~

4.3 Advantages, limitations and perspectives of development of the QST test

The main strength of the QST relies on its simplicity, as the test is rapid to run and doesn't require expensive equipment or laboratory consumables~~(distilled~~ : demineralised water is actually the only consumable required~~)~~. QST measurements can therefore easily be repeated several times for one single plot, to improve the robustness of the result by decreasing both the impact of field microsite heterogeneity and of analytical error. Another point of ~~interest~~ attention is that the QST works on a large structured soil volume (Kopecky cylinders of $100\,\mathrm{cm}^3$ in the present study) whereas most traditional methods apply to a certain amount of small aggregates from a soil previously gently crumbled by hands (**?????**). ~~The~~ On the one hand, the use of a large soil volume may increase the representativeness of the soil sample while decreasing the risk of bias introduced by the selection of soil aggregates from a given size fraction~~(~~: the test then neglects the properties of the soil fraction of inferior or superior equivalent diameter~~).~~ . On the other hand, the test is poorly adapted for a soil that has been crambled by tillage shortly before sampling, for which sampling of a soil volume of $100\,\mathrm{cm}^3$ may be complicated. Currently, the test has not been tested for stone-rich soils, for which the adequacy of the QST needs to be verified. At this point, the relevance of QST curves to assess soil erodibility needs also to be verified.

To promote the adoption of the QST method by a wide public, an ~~opensource R package~~ open-source R-package 'slaker' (**?**) including a web application is currently under development for QST data ~~acquiring~~logging, management and analysis, including the calculation of relevant indicators and statistics from the curves and the provision of some keys of data interpretation. Therefore, the QST has a strong potential for adoption by a widespread community of end-users from soil science laboratories to farmer organisations with no or little expertise in the measurement of soil properties.

Beyond its simplicity and its large adoption potential, the dynamic character of the test is another strong point, since a high density of information stands in one single curve. ~~On the one hand, it has the advantage to provide at once information on the two main mechanisms of soil disaggregation under water (slaking and clay dispersion), and~~ It offers the possibility to ~~calculate a diversity of indicators for curve interpretation, focusing either on~~ extract information either related to one specific mechanism of disaggregation (e.g. $\text{Slope}_{\cancel{max\text{-}60}\,30\text{-}60}$ for slaking and ~~t95~~ t_{95} for clay dispersion) or on the overall structural stability of soil (W_{max}-$W_{\cancel{\theta}t0}$, W_{end} ~~,~~ or AUC). In this regard, the strong linear relationship between W_{max}-$W_{\cancel{\theta}t0}$ and SOC:clay ratio (which can be considered as a proxy for the estimation of the 'potential' structural stability of a soil, **?**, **?**), supports the view that W_{max}-W_{t0} is relevant to evaluate the overall soil resistance to disaggregation in field conditions. ~~This kind of indicator may therefore be more relevant for the overall appreciation of soil structural stability than indicators related to one specific mechanism of soil disaggregation.~~

~~On the other hand, one can stand that the focus of the test is not clearly defined in terms of mechanism of disaggregation as the responses of soil to slaking and clay dispersion overlap. In that respect, a perspective of improvement of the test is to get rid of the interference of air bubbles leaving the sample in the early stages of the QST. This could be reached by measuring soil mass leaving the basket in addition to that remaining in the basket. By removing this 'air release' variable, we hypothesise that the curves would result only from the overlapping effects of slaking and clay dispersion, which would reduce the number of explanatory variables to two and allow for a successful curve modelling , in order to decompose the curves regarding the~~

~~respective contribution of slaking and clay dispersion. Another challenge is that information from one indicator can somehow be contradictory with the information from another indicator from the same curve, as shown in the present study for the OM trial. To tackle this issue, the construction of a QST library to better assess the response of QST indicators to soil management practices and soil properties is necessary to objectify the choice of suitable indicators from the curves and provide keys for their~~ At the moment, curve analysis was limited to the calculation of indicators but curve modelling is another perspective of curve interpretation.

In its current state, the test doesn't provide information on the size of aggregates surviving disaggregation under water, which is of interest to predict soil susceptibility to water erosion. Nevertheless, measurement of residual aggregate size distribution with classic sieving method would decrease the convenience of the test. ~~Coupling the test with a particle size analyser by dynamic image analysis is another perspective of development for rapid determination of size distribution of particles leaving the basket.~~ As it stands, the test doesn't provide any information on soil resistance to ~~raindrop impact. Howeverthis point is not critical as~~ mechanical breakdown. However, soil resistance to ~~raindrop impact~~ sealing and crusting is routinely estimated by ~~pedotransfert~~ pedotransfer functions using pH ~~,~~ in water and SOC and clay contents as input variables (**?**), which appears complementary with the information offered by the QST.

To sum up, the QuantiSlakeTest has ~~many strengths, and many~~ several strengths, some limitations and many questions currently unanswered. Number of perspectives of development exist to tackle the ~~existing~~ current issues and better exploit the ~~QST~~ curves.

5 Conclusions

In this work, we propose a new method to evaluate soil structural stability, the ~~QuantiSlake Test~~ QuantiSlakeTest (QST). It consists in the dynamic ~~weighting~~ weighing of a structured soil sample under water and the calculation of several indicators from the curves to evaluate soil structural stability. The QST presents several advantages. First, it is rapid to run and works with structured soil samples of large size, which improves the representativeness of the sample and allows for multiple field repetitions. Second, the QST doesn't require expensive equipment or laboratory consumables. Third, a high density of information stands in one single curve, with the possibility to extract information either on specific mechanisms of soil disaggregation (slaking ~~and clay dispersion~~ or clay dispersion and differential swelling), or on the overall structural stability of soil. ~~Several perspectives of improvement of the QST are under study, such as the decomposition of the overlapping mechanisms of soil disaggregation by curve modelling and the development of an online program for data management, automated calculation of indicators and statistics from the curves and providing keys of interpretation.~~ Therefore, the test has a strong potential for adoption by a widespread community of end-users from soil science laboratories to farmer organisations with no or little expertise in the measurement of soil properties.

In the present article, ~~we show that the~~ the QST was applied to 35 agricultural soil samples from three long-term experiments in the silt loam region of central Belgium. For these soils, the early mass loss under water ~~is~~ was mainly related to slaking, whereas after soil saturation with water, clay dispersion ~~becomes the dominant process~~ and differential swelling became the dominant processes of soil disaggregation. We found that soil resistance to ~~both slaking and clay dispersion~~ disaggregation is closely related to the SOM status of soil, well-captured by the SOC:clay ratio. From our results, we confirm the validity of the SOC:clay as a proxy for the estimation of soil intrinsic 'potential' structural stability ~~, with the threshold value of 0.1 being a reasonable target for SOM management at field and farm scales for~~ for the soils of central Belgium~~(???). On the other hand, we propose that the early increase in soil mass systematically recorded shortly after introduction of soil in water (W_{max}-W_0) when running QST on cropland soil provides a quantitative measurement representative of soil structural stability as it stands in field conditions. Both parameters are therefore relevant in terms of appreciation of soil resistance to water erosion and structural damage by farm machinery.~~ , as it correlated strongly with QST indicators.

Beyond the absolute amount of SOC for a given level of clay, the response of QST indicators to ~~agricultural~~ soil management practices highlighted that the quality and timing of SOM inputs affects both SOC storage and soil resistance to disaggregation. In the organic matter trial, for similar total SOC inputs, farmyard manure favoured the total SOC content and had the best soil resistance to slaking whereas green manure and restitution of crop residues improved soil resistance to clay dispersion and differential swelling the most. ~~We conclude~~ This supports the view that living and labile biomass is more efficient in decreasing clay dispersivity whereas soil resistance to slaking relates to total SOC content. This underlines that the choice of indicators for the interpretation of QST curves must be done with great caution, as indicators from the start and the end of the curve may lead to conflicting conclusions.

Appendix A: Supplementary matrices of correlation coefficients

A1 Autocorrelations between QST indicators

Table A1. Autocorrelation coefficients between QuantiSlakeTest indicators

	Slope 0-max	tmax	Wmax-Wt0	Slope max-30	Slope 30-60	Slope 60-30	Slope 300-600	Slope max-60	Slope max-300	Slope max-600	dt max-25	dt 25-50	dt 50-75	dt 75-90	t50	t75	t90	t95	Wend	AUC
Slope 0-max	1.00	-0.57	-0.36	-0.51	-0.36	0.06	0.35	-0.52	-0.42	-0.35	-0.60	-0.49	-0.38	-0.33	-0.57	-0.48	-0.47	-0.37	-0.36	-0.42
tmax	-0.57	1.00	0.88	0.78	0.64	0.04	-0.46	0.84	0.74	0.65	0.91	0.82	0.71	0.52	0.91	0.84	0.78	0.71	0.64	0.75
Wmax-Wt0	-0.36	0.88	1.00	0.71	0.48	0.09	-0.27	0.72	0.66	0.61	0.72	0.54	0.49	0.49	0.67	0.60	0.62	0.61	0.58	0.67
Slope max-30	-0.51	0.78	0.71	1.00	0.50	-0.16	-0.42	0.94	0.71	0.65	0.82	0.66	0.52	0.40	0.78	0.67	0.62	0.54	0.62	0.74
Slope 30-60	-0.36	0.64	0.48	0.50	1.00	0.27	-0.32	0.76	0.81	0.75	0.56	0.62	0.50	0.22	0.61	0.58	0.47	0.35	0.77	0.81
Slope 60-30	0.06	0.04	0.09	-0.16	0.27	1.00	0.46	-0.02	0.51	0.60	-0.25	-0.07	-0.06	-0.08	-0.17	-0.11	-0.11	-0.15	0.61	0.48
Slope 300-600	0.35	-0.46	-0.27	-0.42	-0.32	0.46	1.00	-0.45	-0.16	0.04	-0.70	-0.50	-0.45	-0.39	-0.63	-0.56	-0.54	-0.56	0.02	-0.15
Slope max-60	-0.52	0.84	0.72	0.94	0.76	-0.02	-0.45	1.00	0.85	0.77	0.84	0.74	0.59	0.38	0.83	0.73	0.65	0.54	0.76	0.86
Slope max-300	-0.42	0.74	0.66	0.71	0.81	0.51	-0.16	0.85	1.00	0.98	0.59	0.60	0.48	0.29	0.62	0.57	0.50	0.39	0.98	1.00
Slope max-600	-0.35	0.65	0.61	0.65	0.75	0.60	0.04	0.77	0.98	1.00	0.46	0.50	0.39	0.22	0.50	0.46	0.40	0.29	0.99	0.98
dt max-25	-0.60	0.91	0.72	0.82	0.56	-0.25	-0.70	0.84	0.59	0.46	1.00	0.84	0.66	0.48	0.96	0.84	0.76	0.69	0.46	0.61
dt 25-50	-0.49	0.82	0.54	0.66	0.62	-0.07	-0.50	0.74	0.60	0.50	0.84	1.00	0.85	0.55	0.95	0.94	0.86	0.76	0.49	0.60
dt 50-75	-0.38	0.71	0.49	0.52	0.50	-0.06	-0.45	0.59	0.48	0.39	0.66	0.85	1.00	0.57	0.78	0.96	0.89	0.87	0.34	0.47
dt 75-90	-0.33	0.52	0.49	0.40	0.22	-0.08	-0.39	0.38	0.29	0.22	0.48	0.55	0.57	1.00	0.53	0.59	0.86	0.83	0.17	0.28
t50	-0.57	0.91	0.67	0.78	0.61	-0.17	-0.63	0.83	0.62	0.50	0.96	0.95	0.78	0.53	1.00	0.92	0.84	0.76	0.49	0.63
t75	-0.48	0.84	0.60	0.67	0.58	-0.11	-0.56	0.73	0.57	0.46	0.84	0.94	0.96	0.59	0.92	1.00	0.92	0.87	0.43	0.57
t90	-0.47	0.78	0.62	0.62	0.47	-0.11	-0.54	0.65	0.50	0.40	0.76	0.86	0.89	0.86	0.84	0.92	1.00	0.95	0.35	0.50
t95	-0.37	0.71	0.61	0.54	0.35	-0.15	-0.56	0.54	0.39	0.29	0.69	0.76	0.87	0.83	0.76	0.87	0.95	1.00	0.23	0.38
Wend	-0.36	0.64	0.58	0.62	0.77	0.61	0.02	0.76	0.98	0.99	0.46	0.49	0.34	0.17	0.49	0.43	0.35	0.23	1.00	0.98
AUC	-0.42	0.75	0.67	0.74	0.81	0.48	-0.15	0.86	1.00	0.98	0.61	0.60	0.47	0.28	0.63	0.57	0.50	0.38	0.98	1.00

Table A2. Correlation coefficients between soil properties, Mean Weight Diameters (MWD) and percentages of macro-aggregates (MA) from the three tests of Le Bissonnais (1. Fast wetting; 2. Slow wetting; 3. Mechanical breakdown in water after rewetting with EtOH) and soil properties. The gradient of colours relates to the positive (blue) or to the negative (orange) relative amplitude of correlation coefficients.

	SOC	Clay	SOC:Clay	pH	Bulk density
MWD 1	0.75	-0.35	0.67	-0.06	-0.29
MWD 2	0.70	-0.12	0.48	0.16	-0.30
MWD 3	0.11	0.52	-0.33	-0.31	0.31
MA 1	0.63	-0.43	0.64	-0.25	-0.20
MA 2	0.43	0.19	0.05	-0.08	0.09
MA 3	-0.07	0.66	-0.55	-0.39	0.44

A2 Soil properties and indicators from Le Bissonnais approach

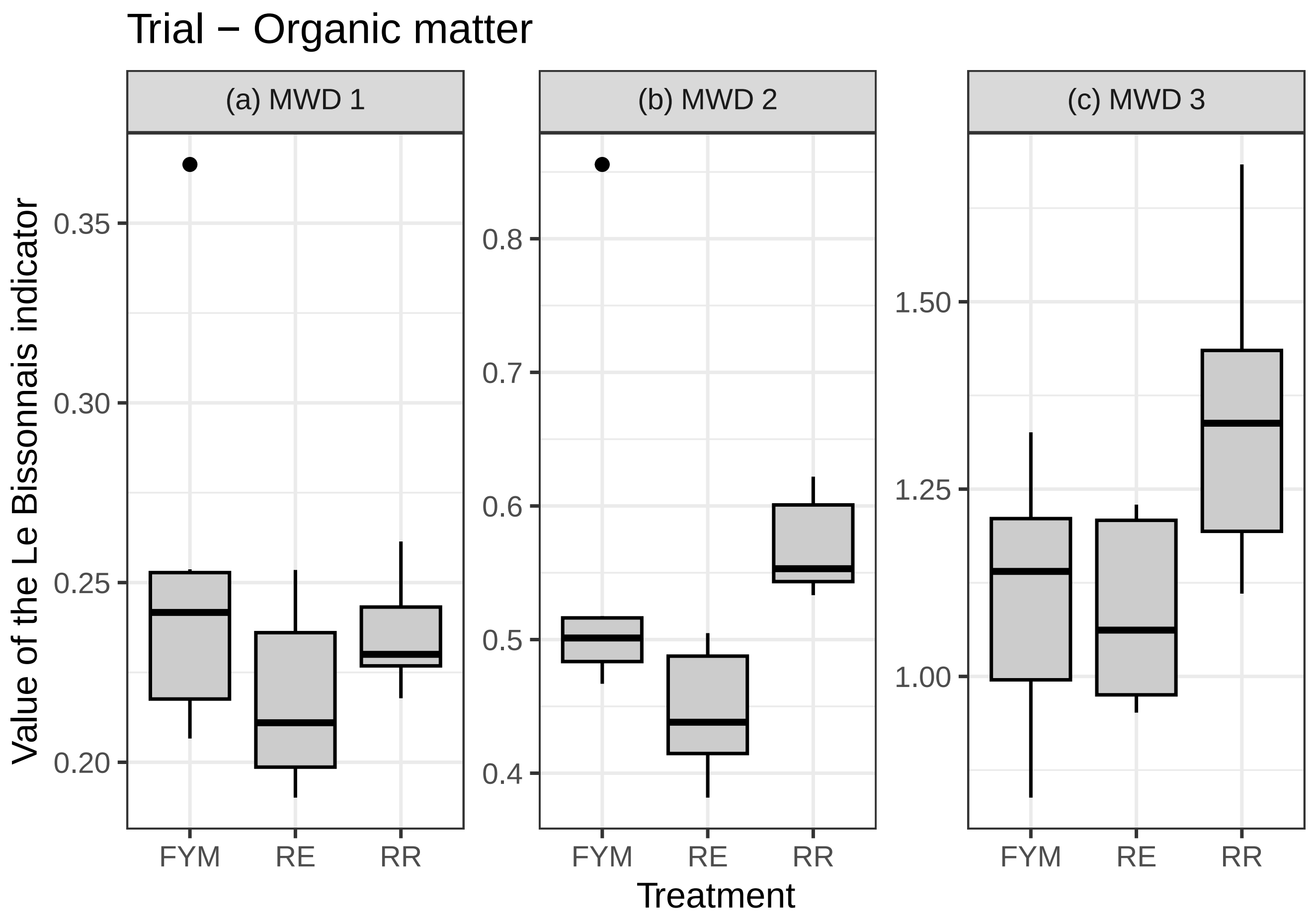

Figure B1. Boxplots of the three MWD from Le Bissonnais test against treatments of OM input for the soils from the organic matter trial, ’residue exportation’ (RE), ’farmyard manure’ (FYM) and ’residue restitution’ (RR).

Appendix B: Le Bissonnais soil aggregate stability under contrasting soil management practices

B1 Organic matter trial

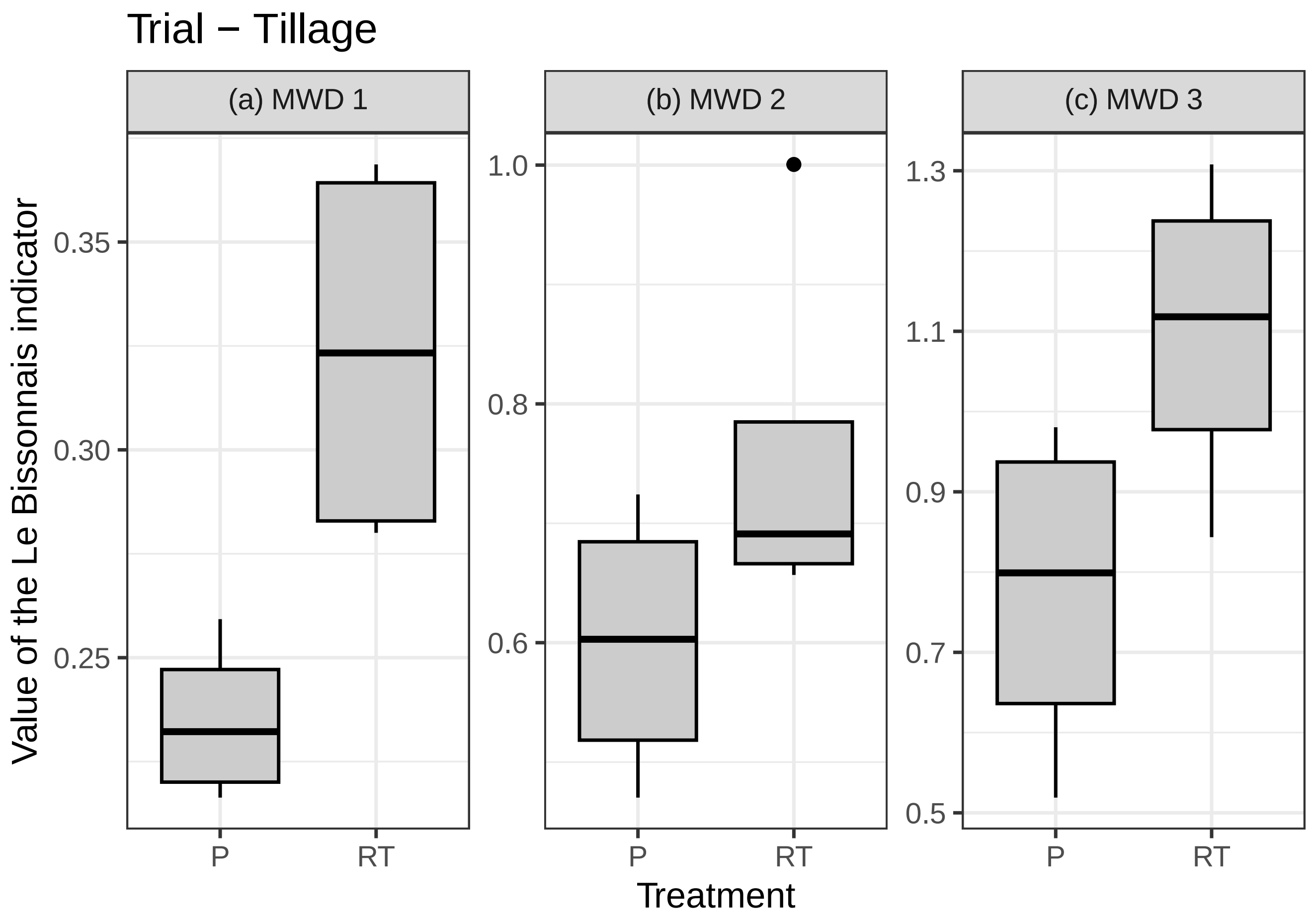

Figure B2. Boxplots of the three MWD from Le Bissonnais test against tillage treatments, ploughing (P) and reduced tillage (RT) for the soils from the tillage trial.

B2 Tillage trial

Code availability. R-package - slaker - Analysing the data of QuantiSlakeTest approach. R-package and Web Application, https://gitlab.com/FrdVnW/slaker ; Notebook with codes, figures and tables - qst-openscience, https://frdvnw.gitlab.io/qst-openscience/

Data availability. Data repository in the SlakingLab community on Zenodo https://doi.org/10.5281/zenodo.7142458

Code and data availability. Full git repository - qst-openscience https://gitlab.com/FrdVnW/qst-openscience

Video supplement. A visualisation of the QuantiSlakeTest, comparing two contrasted samples (tillage / conservation tillage) and curve generation ; Tuto slake 1, in french ; Tuto slake 2, in french

Author contributions. FV and BH planned the sampling campaign and the measurements, analysed the data, wrote the manuscript draft and reviewed and edited the manuscript.

Competing interests. The authors declare no competing interests.

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