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Changes in topsoil organic carbon content in the Swiss leman region cropland from 1993 to present. Insights from large scale on-farm study

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ABSTRACT

Increasing cropland topsoil organic carbon *(SOC)* content is a key goal for soil improving quality and adaptating soils to climate change. Moreover, the short term potential of climate mitigation by carbon sequestration is mostly attributed to increasing topsoil *SOC* content (Balesdent and Arrouays, 1999; Chambers et al., 2016; Minasny et al., 2017; Balesdent et al., 2018). However, the possibility to increase *SOC* content is highly disputed in current literature which is mostly based on field experiments.

We quantified the on-farm *SOC* content deficit and *SOC* content change rate of cropland topsoil (0–20 cm) from western Switzerland using the data bases of Geneva and Vaud cantons containing more than 30,000 topsoil analyses, performed every ten years on every cultivated field of the region since 1993. *SOC* deficit was estimated as the amount of *SOC* necessary to reach the 0.1 *SOC*:clay ratio considered as the minimum required *SOC* amount for acceptable soil quality. Cropland topsoils of the Vaud and Geneva cantons displayed a 20% and 70% *SOC* content deficit, respectively.

In both cantons, the range of observed rates of change in *SOC* content from 1993 to present was very large, from −30 to +30‰ per year, with a median value of 0. However, the time trends showed a highly significant linear increase of rates from −5‰ to +6‰ per year on average, in 1995 and 2015, respectively, with no change in *SOC* content reached by 2005–2007.

These trends were attributed to the Swiss agri-environmental schemes applied at the end of 20th century, namely mandatory cover crops and minimum rotations of 4 crops. Further, *SOC* content increase was accordant with the continuing adoption of minimum tillage, conservation agriculture and multi-species intense cover crops.

These findings oppose to those obtained in Swiss long-term experiments, which emphasizes the need to use on-farm information when adressing agriculture policy, climate mitigation or soil quality management issues.

1. Introduction

Soil organic carbon (*SOC*) is a major driver of soil quality, in particular of its chemical and physical fertility (Bünemann et al., 2018; Kay, 1998; King et al., 2020). Moreover, the millennium assessment (Hooper et al., 2005) revealed that soils are the corner stone of terrestrial ecosystem services. Since then, soil scientists and the scientific community warned about soil degradation jeopardizing the future of mankind on earth (IPCC, 2019). In cropland, many processes such as erosion and compaction result in soil degradation (Montanarella et al., 2016; Tóth et al., 2008), however, a major process of degradation is the loss of *SOC*, owing to its key role for soil fertility, soil physical properties and structure vulnerability (Johannes et al., 2017; King et al., 2020), or soil compaction mitigation (Goutal-Pousse et al., 2016).

Intensified agriculture, which was promoted in the second half of 20th century with objectives such as increase of the food production, decrease of the food prices, and limitation of the required manpower, caused a sharp decrease in topsoil *SOC* content, estimated up to 50–70% of initial topsoil *SOC* content (Lal, 2011; Sanderman et al., 2017). *SOC* loss was mostly attributed to intense soil disturbance, shortening of the rotations lengths and export of the crop residues (Reicosky, 2003; Smith et al., 2012; West and Post, 2002). Several considerations including decline of soil quality and provision of ecosystem services (Power, 2010; Swinton et al., 2007; Tilman, 1998) lead to reconsider in depth the intensified agriculture model.

Climate change issues actually increased the pressure on agriculture.

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On one hand, agriculture is a major contributor to greenhouse gas emissions (FAO, 2020). On the other hand, the control of atmospheric carbon dioxide (CO_2) levels is growingly considered to depend on the Negative Emission Technologies (NETs), as long as the reduction of fossil emissions remains a fiction (IPCC, 2018). The 4 per 1000 initiative (https://www.4p1000.org) highlighted the potential for C sequestration in soils, defined as "the process of transferring CO2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter (humus)" Olson et al. (2014), by stressing that the yearly emissions represent a 4‰ fraction of the total estimated *SOC* (Balesdent and Arrouays, 1999), which arithmetically leads to suggest that increasing *SOC* content by +4‰ every year would represent the most powerful NET (Minasny et al., 2018; Soussana et al., 2019). Reviewing the different NETs and their potential to meet COP21 agreement, the European Academies of Science Advisory Council (EASAC, 2019; 2018) concluded that C sequestration in soils is one of the most technologically credible, cost-effective and currently viable approach to support ecological transition towards carbon neutrality.

Accordingly a considerable amount of literature was dedicated to C sequestration in soils and the possible practices to achieve it. The literature, however, is highly controversial, with respect to the appropriate methods and their real potential (Baveye et al., 2018; Lal, 2020; Lugato et al., 2018; Minasny et al., 2017; Paustian et al., 2019; Powlson et al., 2014; van Groenigen et al., 2017). Though some research emphasizes the potential to achieve soil C sequestration based on technologies independent form farming practices, such as deep ploughing or the burial of biochars (Keel et al., 2019; Vaccari et al., 2011; Windeatt et al., 2014), most studies focused on conservation agriculture (CA) methods, including no-till and direct seeding, or agroforestry, either underlying their potential to reach *SOC* content increase goals, or concluding that these goals would not be achieved (Chenu et al., 2019; Gonzalez-Sanchez et al., 2019; Lal, 2015; Powlson et al., 2016; Zhang et al., 2014). One of the major weaknesses of this research is that most results are obtained from long term experiments in research station conditions, which are poorly representing on-farm field processes (Cook et al., 2013; Govaerts et al., 2009; Hall et al., 2005). There is, therefore, a need for more on-farm information on the cropped soil C sequestration or loss.

Complementary to the question of possible C sequestration rates expected from different practices is the question of the sequestration potential of the soils, namely the additional SOC that can be stored in soil, usually calculated as the difference between the maximum SOC stocks and current SOC stocks in soil layers or profile (Chen et al., 2019). There is little knowledge on the minimum required *SOC* level for cropland soils with respect to soil quality, and to what extent existing cropping systems could meet such requirements. In a seminal paper based on French and Polish soil databases, Dexter et al., 2008 defined the optimal *SOC* content as 0.1 of the clay content, which they related to the complexation capacity of *SOC* on clay. In their review, Wiesmeier et al., 2019 identified different factors for carbon storage and stressed the importance of *SOC* complexation on clay. In Swiss cropland, Johannes et al., 2017 showed that the 0.1 SOC:clay w/w ratio defined the limit between damaged and acceptable soil structure on average, with values of 1:8 for average good structure and 1:13 for severely degraded structure. The same limits were found from the analysis of a large database of UK soils (Prout et al., 2020). The soils from these studies were sampled at any season and any step of the rotation. Therefore, their average structural state reflected the combination of their resistance and resilience properties towards physical impacts, namely their structure vulnerability (Kay, 1998; Seybold et al., 1999), which led Fell et al., 2018 to call the *SOC*:Clay ratio the structure vulnerability indicator (*SVI*). Because 0.1 is the *SVI* limit for acceptable structure quality, it can be used to calculate the minimum required *SOC* content for soil quality management (Prout et al., 2020).

We hypothesized that on-farm results may provide interesting insights on C dynamics in cropland soils. This study was carried out in the framework of the agricultural parts of the climate plans of Vaud and Geneva cantons in Switzerland. We used farm-fields soil analyses data bases to compare the observed *SOC* content to the minimum required to reach a 0.1 *SVI*, and the observed *SOC* content change rates for thousands of cropland fields in the past two decades.

2. Material and methods

The study was performed on the cropland topsoil (0–20 cm layer) of Geneva and Vaud cantons, western Switzerland (Fig. 1). The dominant soil type was cambi-luvisol (IUSS Working Group WRB, 2014), developed on morains mixed to a variable proportion of molasses. According to the regional data bases (see below) their clay content ranged from 5.3% to 42.9% (w.w^{-1}), though most of the soils had their clay content in the 15–30% range (Fig. 2). Because of the post-glacial morainic origin of the materials and the low level of weathering, the clay minerals were herited, of large size, show limited Cation Exchange Capacity and mixed mineralogy (Illite, vermiculite and interstratified; personal data). There is a large diversity of cropping practices in the region. The minimum rotation length is 4 year since 1998. Rotations include different cereals such as wheat and barley, and rapeseed. The major spring crops are maize, sugar beat and potatoes. About 10% of the fields are under direct seeding. Temporary pastures are included in the rotation when there is livestock on the farm, which is frequent in Vaud but not in Geneva.

2.1. Available data bases

To receive ecological subsidies, Swiss farmers must analyse the 20 cm topsoil of every field each ten years at least. One of the mandatory analyses is *SOC*, and the recommended method was sulfo-chromic oxidation of organic matter following (Walkley and Black, 1934). Farmers are expected to collect a composite sample from each field to perform this analysis in a certified laboratory. The corresponding results were stored in a GIS database in Geneva canton, while they were stored in a classical database in Vaud canton. In this latter case, plots were identified by the location, the farmer and the plot names. Regulation of agriculture and incentives for farmers are based on both federal and canton decisions in Switzerland, while advising services are managed at canton level. Because agriculture structure, history and some agricultural regulation differ between cantons, we distinguished the two cantons in the results section of this study, before considering the general patterns and the cantons specificities in the discussion.

The two databases contained 33,620 cropland soil sample analyses (permanent pastures, orchards and vineyards were not taken into account), each of them representing a composite from one field, with *SOC* content (% g.g^{-1}) analysis obtained from sulfo-chromic oxydation as defined in the federal recommendations for soil analyses (Agroscope, 1996). The time series started in 1993 in both cases. The quality of the sampling and corresponding minimum detectable change from field scale to farm and canton scales (MDC) were evaluated in a separate study (Deluz et al., 2020). In Geneva canton, the farmers mostly used a double-diagonal trajectory or random sampling, with a median value of 7 aliquots, to make the composite, while in Vaud canton, thanks to more precise guidelines, most farmers collected 15 aliquots on the two diagnonals of the field, thus standing very close to the best practices recommending to sample 20 aliquots on the two diagonals (Deluz et al., 2020).

2.2. Data selection

Since we adressed the general case of cropland cambi-luvisols, we had to exclude particular cases such as some drained peatland or marshes spots (Vaud canton), well known to lose *SOC* (Wüst-Galley et al., 2020), sandy soils for which the *SVI* threshold have no meaning, and possible data errors. Therefore, we applied a data selection based on Tukey's 1.5 Inter-Quartile Range (IQR) exclusion method (Tukey,

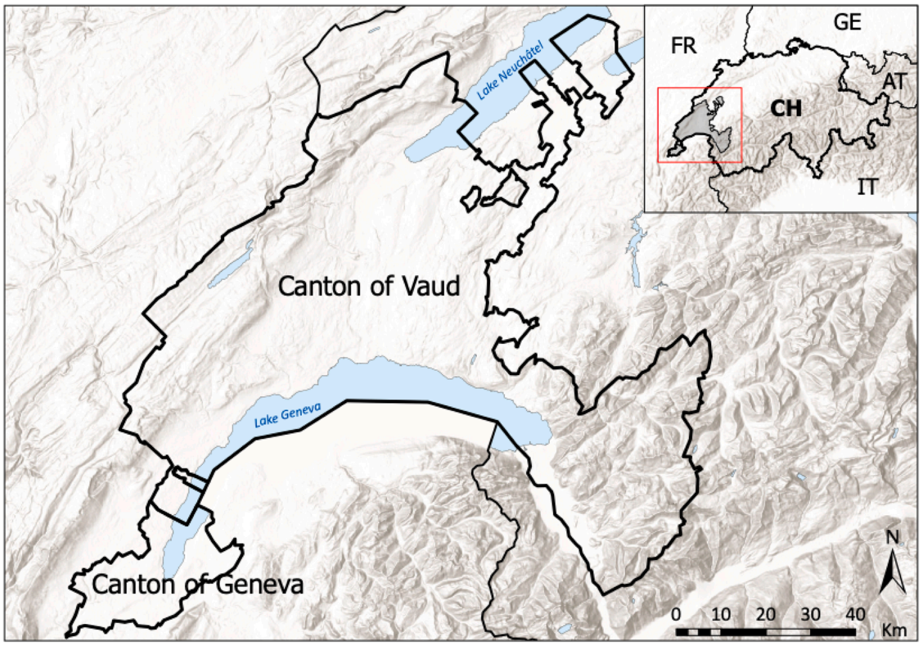

Fig. 1. Map of Switzerland with location of the cantons of Geneva and Vaud.

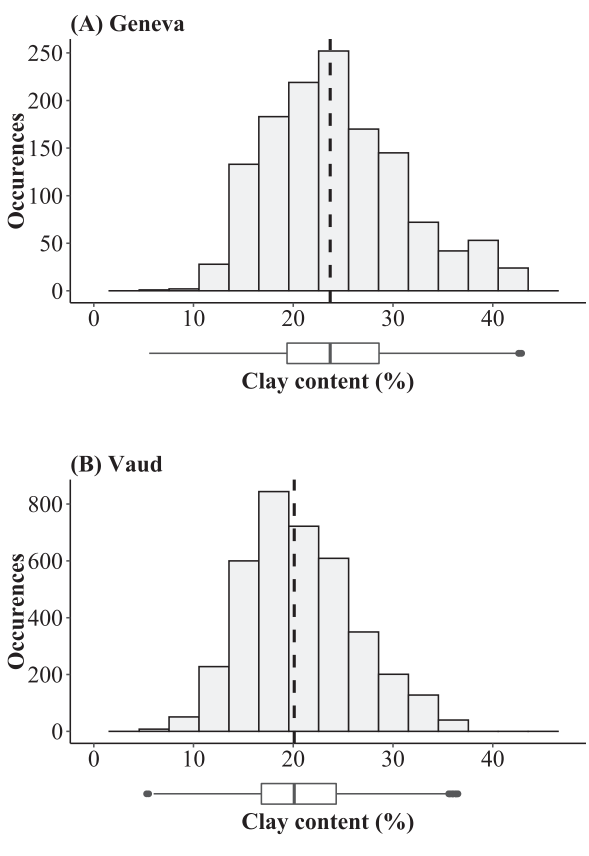

Fig. 2. Histogram and boxplot of clay content as determined in the 0–20 cm topsoil of cropland fields from (A) Geneva (1324 fields) and (B) Vaud (3781 fields) cantons. Dashed vertical line: median value.

1977). This selection was applied on *SOC* content, clay content, and *SVI*. The excluded *SOC* content analyses were larger than 3.8%, which corresponded to the observed lower value in drained marsh soils of the region (locally called "black land"). They represented 7% of the data, and exclusion did not change *SOC* median values. The resulting *SOC* distribution still showed outliers on the larger end (Fig. 3) contrarily to

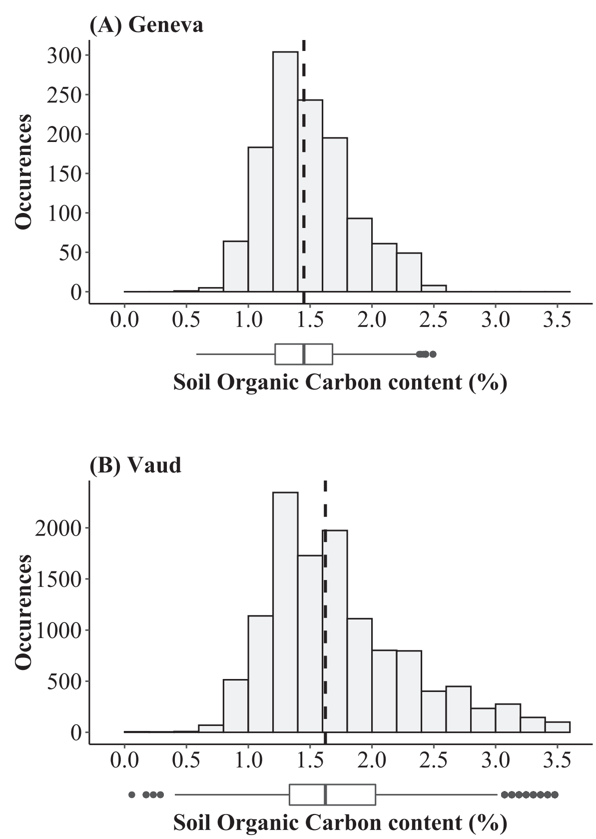

Fig. 3. Histogram and boxplot of *SOC* content as determined in the 0–20 cm topsoil of cropland fields from (A) Geneva (1206 fields) and (B) Vaud (12108 fields) cantons. Dashed vertical line: median value.

clay content (Fig. 2) and *SVI* (Fig. 4), however, these values were kept since they may not correspond to drained marses spots. There was 5273 fields with available clay content (determined by sedimentation with pipette method, Agroscope, 1996), and 5105 (97%) after outlier exclusion (pure sandy soils and some heavy clay), which did not change the median values. Further outlier selection on the *SVI* values excluded 1.5% of the fields only.

We also distinguished the results obtained from 2007 to present, which yielded 1206 and 12,108 *SOC* content results for Geneva and Vaud cropland, respectively. Combined with clay content when available, this allowed to calculate the 2007-to-present *SOC*:clay ratio of 523 and 1469 fields from the Geneva and Vaud cropland, respectively.

SOC deficit

The minimum deficit in *SOC* was calculated for each field as the amount of *SOC* necessary to reach the minimum acceptable *SVI*, namely 0.1 SOC:clay ratio:

$$SOCdeficit = (SVI - 0.1) \times claycontent$$

SOC annual change rate

To calculate the annual rate of change (*ARC*) of *SOC* content we selected from the full data base (i.e. 1993-present) all fields for which consecutive analyses were available. At some occasion farmers analysed their soils more frequently than the 10 years mandatory time lag. Couples of analyses separated by less than 5 year were discarded. The average time lag between two consecutive analyses in the remaining data set was 9.9 years. Moreover, in Geneva, it was possible to control from the GIS and aerial photographs that the field limits were not modified between two consecutive analyses. The *ARC* of each field between two consecutive analyses was calculated in ‰ to allow better comparison with studies referring to the 4 per 1000 initiative using:

$$SOC_{fin} = SOC_{init} \times (1 + ARC)^n$$

With SOC_{init} and SOC_{fin} the two consecutive analyses and n the number of years between these two analyses. Which yielded:

$$RC(‰) = 1000 \times \left(\left(\frac{SOC_{fin}}{SOC_{init}} \right)^{\frac{1}{n}} - 1 \right)$$

Applying Tukey's IQR outlier exclusion to the *ARC* values excluded 5.5% of the results, which yielded 499 and 1807 *ARCs* from 1993 to present, and 184 and 754 *ARCs* from 2007 to present, for Geneva and Vaud, respectively. Excluded *ARC* values were smaller than −30‰ or larger than +30‰. Keeping them in the data set did not change the median *ARC* and the regressions of *ARC* with time, however. *ARC* values were attributed the midyear between the two analyses. For instance, if the soil was analysed in 2019 and 2009, the corresponding *ARC* was attributed to 2014 in the following. In some fields, several successive *ARC* values were available when more than two consecutive analyses were available. The change in *ARC* with time was, therefore, plotted, and the LOWESS local regression prediction interval was calculated to check for linearity (Cleveland and Devlin, 1988).

In a preliminary study, (Deluz et al., 2020) determined the "best practice" guidelines for farmers to sample a composite in their fields, and showed that the corresponding MDC of *SOC* content change was 0.1% ($w.w^{-1}$). We applied this value to calculate the number of years *N* between two consecutive *SOC* content analyses for *SOC* content change to be detectable, based on the observed *ARC* and the *SOC* content of the field, using the condition:

$$|SOC_{fin} - SOC_{init}| > 0.1$$

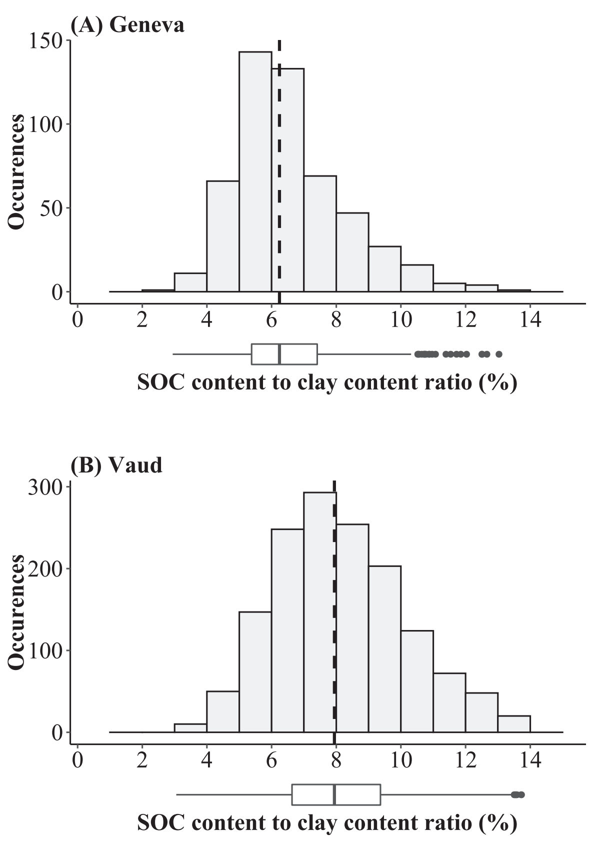

Fig. 4. *SOC* to clay ratio (SVI) in the 0–20 cm topsoil of cropland fields from Swiss cantons of (A) Geneva (523 fields) and (B) Vaud fields (1469 fields). Dashed vertical line: median value.

3. Results

The *SOC* content values of the 0–20 cm topsoil in Geneva and Vaud cropland fields are presented in Fig. 3. Median *SOC* topsoil content was 1.45 and 1.63% on average for Geneva (1206 fields) and Vaud (12108 fields), respectively (see Table 1 for details). In Fig. 4 are presented the *SVI* values obtained for 523 fields in Geneva and 1469 fields in Vaud. The median *SVI* was 6.24% in Geneva and 7.94% in Vaud. *SVI* is particularly low in Geneva where *SOC* content should increase by 70% to reach the 0.1 minimum *SVI* for acceptable structure vulnerability. Vaud median *SVI* was also below the 0.1 target value, though larger than in Geneva (Table 1). The *SOC* content median values of these data sets were unchanged compared to the larger data sets used in Fig. 3.

The *SOC* content deficits calculated based on the *SVI* values and the 0.1 target (Eq1) are presented in Fig. 5 in percentages of the observed *SOC* content value. The median *SOC* content deficits were 0.90% and 0.48% of the observed *SOC* content median, for Geneva and Vaud, respectively (Table 1).

The *ARC* values calculated on the full data set (1993-present) according to Eq3 are presented in Fig. 6 after exclusion of the outliers, for a total of 496 and 1793 fields in Geneva and Vaud, respectively. Median values were at neutrality (*ARC* = 0‰) but ranged from −30‰ to +30‰ for both cantons.

The *ARC* values as a function of mid-year of analyses are presented in Fig. 7. The *ARC* time trends presented very similar patterns in the two cantons, namely a highly significant linear increase from −3.8 and −3.7‰ in 1998 for Geneva and Vaud, respectively, to +5.5 and +7.8‰ in 2015. The cantons average *ARC* became positive in 2007 and 2005, respectively. Extrapolating the linear relationships fitted in Fig. 7 to 2020 leads to *ARC* values of +6.3 and +8.5‰ in Geneva and Vaud, respectively. Though the relationships between *ARC* and time were highly linear according to LOWESS prediction intervals, *ARC* showed a faster growth before 2001, then remained neutral (*ARC* = 0) until 2007 before increasing again in Geneva, while it increased more regularly

Table 1
Summary statistics. Soil organic carbon content (*SOC*) (%), clay content (%), *SOC* to clay ratio (%), *SOC* content deficit (%) compared to the (0.1) *SOC*:clay ratio, and annual *SOC* content change rates (‰) for Geneva and Vaud cropland fields.

	n (fields)	Minimum	Median	Mean (+SE)	Maximum
SOC (Geneva) (% w. w^{-1})	1206	0.58	1.45	1.49 (0.35)	2.49
SOC (Vaud) (% $w.w^{-1}$)	12,108	0.060	1.62	1.74 (0.57)	3.48
Clay (Geneva) (% g. g^{-1})	493	11.00	23.20	23.43 (5.37)	39.08
Clay (Vaud) (% g. g^{-1})	1265	7.40	19.60	20.28 (5.34)	35.70
SOC:clay ratio (Geneva) (%)	493	2.94	6.24	6.57 (1.74)	13.04
SOC:clay (Vaud) (%)	1265	3.05	7.94	8.13 (2.02)	13.73
SOC deficit (Geneva) (%)	493	0.02	0.90	0.90 (0.44)	2.08
SOC deficit (Vaud) (%)	1265	0.00	0.48	0.55 (0.37)	1.63
Annual *SOC* content change rate (Geneva) (‰)	496	−29.20	0.00	−0.28 (11.42)	+29.04
Annual *SOC* content change rate (Vaud) (‰)	1793	−30.15	0.00	0.84 (11.69)	+32.60
Annual *SOC* content change rate (Geneva) (‰) (post 2007)	184	−28.95	+1.74	+2.01 (11.71)	+28.04
Annual *SOC* content change rate (Vaud) (‰) (post 2007)	754	−30.16	+3.41	+3.72 (11.59)	+32.60

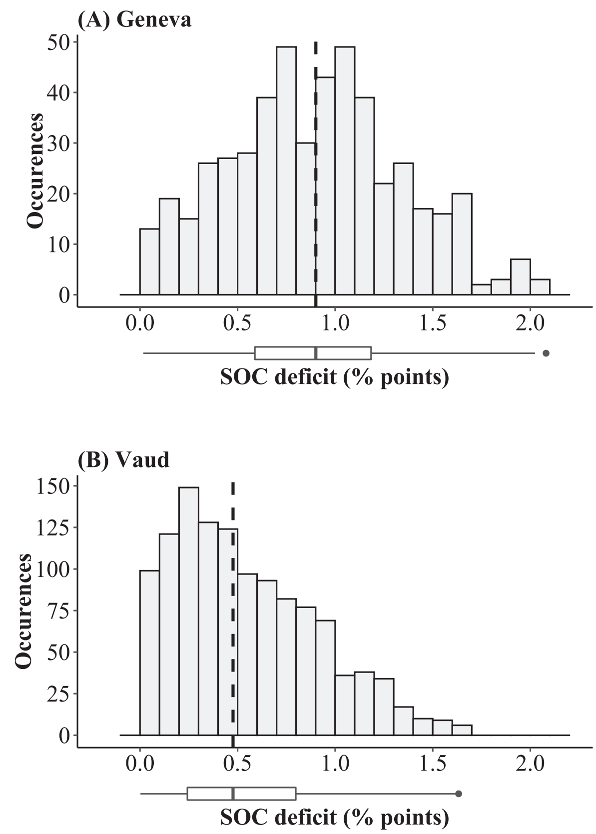

Fig. 5. *SOC* content deficit in % of the *SOC* content of the 0–20 cm topsoil of cropland fields from (A) Geneva (493 fields) and (B) Vaud (1265 fields) cantons as determined by the difference between the observed value and the 0.1 Structure Vulnerability Index threshold value. Dashed vertical line: median value.

from 2002 to present in Vaud.

In Fig. 8 are presented the *ARC* values calculated using samples analyzed after 2006 only. Compared to Fig. 6, *ARC* median value increased from neutrality to +1.74 and +3.41‰, for Geneva and Vaud, respectively, though the range of observed *ARCs* remained unchanged.

4. Discussion

Many regional studies on SOC content dynamics have collected and compared SOC content analysis results either from national inventories at (generally) long time intervals or from a limited number of field (Clermont-Dauphin et al., 2005; Collier et al., 2020; Goidts and van Wesemael, 2007; Gosling and Shepherd, 2005; Wesemael et al., 2011). We are not aware, however, of comparable data sets, namely *SOC* content analysed every ten year, at field scale on all the cropland rather than small plot scale (e.g. Goidts et al., 2009: Gubler et al., 2019).

The *SOC* content deficits calculated using the difference between the observed *SVI* and the 0.1 target are according with the estimations of *SOC* loss under intensive agriculture compared to natural situations (Lal, 2011). In the case of Geneva, a canton with few livestock and temporary pasture, hence limited manure application, an increase of 70% in *SOC* content is required in order to reach an acceptable *SVI*. Recalling that achieving a +4‰ increase in *SOC* content for 30 years would only allow for a total increase of 13% of the *SOC* content, it is clear that the expected increase of *SOC* content with respect to soil quality is much more demanding than achieving the 4‰ climate target. This latter, however, applies at least to the 0–40 cm layer (Minasny et al., 2018). *SOC* content deficit per ha was smaller in Vaud, where livestock production was traditionnaly more present, but cropland represents a much larger area, thus resulting in larger total deficit. By using the average *SOC* content and bulk density values of the 0–20 cm topsoil in these cantons (Table 1), the deficit in total *SOC* stock was estimated at 650000 t and 2000000 Mg CO_2 equivalent, for Geneva and Vaud, respectively. In Geneva, we applied the same method at field level before cumulating the deficit at cropland scale, which led to a similar result (not shown) as expected considering the large number of fields which averages the variations in field characteristics. Therefore, the average *SVI* at regional scale can be used to estimate the sequestration potential. Litterature suggests that the *SVI* is not expected to be larger and, therefore, the *SOC* content deficit would not be smaller, in many European soils (Bellamy et al., 2005; Dexter et al., 2008; Prout et al., 2020). A *SVI* of 0.1 might be considered as out of reach for farmers based on the observed mean *SVIs*. However, it is already exceeded by many farm fields, in particular in Vaud canton (Fig. 4). Moreover, fields with *SVI* larger than 0.1 can show positive *ARC* values (see below).

Observed *ARC* ranged from −30‰ to +30‰ in both cantons with similar distribution, despite the different *SVI* distributions. The median *ARC* value was positive for the 2007 to present period, though neutral for the whole 1993-to-present data set. The positive *ARC* values were close to the reported range at earth scale according to (Minasny et al., 2017). Indeed, more than 20% of the fields showed a *ARC* larger than +15‰ in Geneva (Fig. 6), which is the objective of Geneva's climate plan for cropland soils (Republic and Canton of Geneva, 2017, p. 2). For instance, a *SOC* content of 1.5% and a clay content of 25% (Geneva canton mean values) yields a 0.06 *SVI* (Geneva canton mean *SVI*), while a 2.5% *SOC* content is expected to reach a 0.1 *SVI*. This threshold would be exceeded after 35 years with a 15‰ *ARC*. These observations oppose to the conclusions of Keel et al., 2019, based on results obtained on the 0–20 cm topsoil layer in Swiss LTEs, that *ARC* as large as +4‰ or even

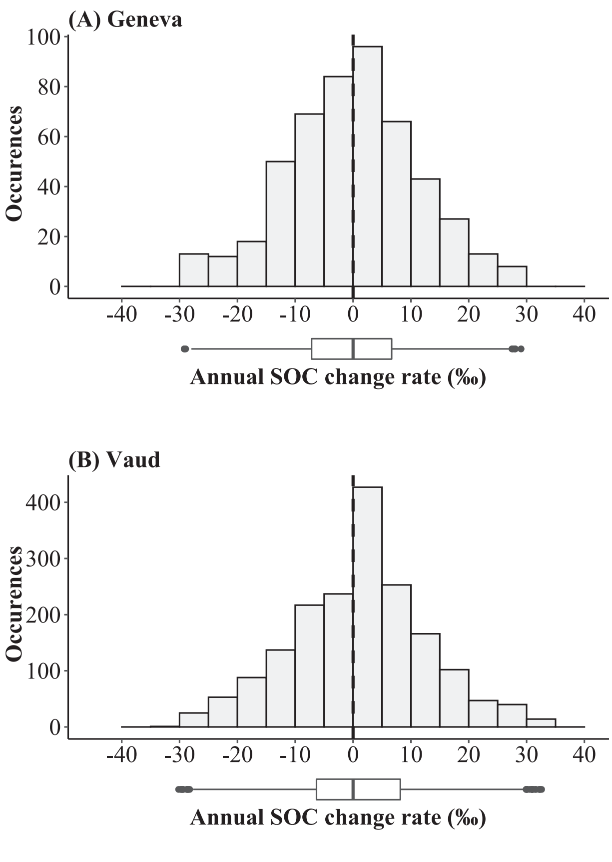

Fig. 6. Annual *SOC* content change rates *ARC* in the 0–20 cm topsoil of cropland fields from (A) Geneva (496 fields) and (B) Vaud (1793 fields) cantons over the 1993–2019 period. Dashed vertical line: median value.

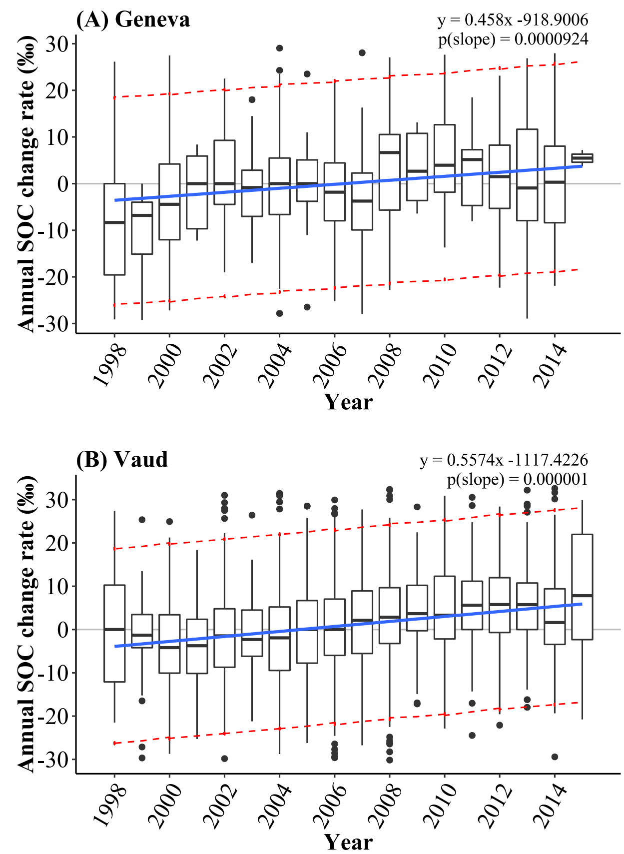

Fig. 7. Annual *SOC* content change rates of the 0–20 cm topsoil of cropland fields over the 1993–2019 period for (A) Geneva (496 fields) and (B) Vaud (1793 fields) cantons as a function of the average year between two analyses. Solid line: linear regression. Dashed line : 95% local regression prediction interval.

positive were out of reach in Swiss agriculture. Such a contradiction emphasizes the need to make distinction between LTE and on-farm observations. In the later case, the different practices – for instance tillage and cover crop, are not separated but linked via the cropping system, and these practices are continuously changing with time, including upon the development of self expertise of farmers. Contrarily, LTEs aim to decorrelate the different factors, and keep constant practices with time, which allows to analyse separately the effect of different practices. Therefore, LTEs results can be very discrepant with on-farm observations, as highlighted here, and one should be very cautious before transferring LETs results and conclusions to farm-field level (Govaerts et al., 2009; Hall et al., 2005). In our opinion, this restriction is not always made clear in the literature, which leads to deliver confusing or misleading messages to decision makers.

The change in *ARC* with time was highly significant with slope p-values smaller than 0.0001 in both cantons (Fig. 6). Accordingly, the difference between average *ARC* values before and after 2007 (Table 1) was highy significant (p-value less than 0.001). This significance level is obtained thanks to the large number of observations, thus highlighting the potential of including as many fields as possible based on farmers' sampling. Such data sets result from the Swiss mandatory soil analyses policy, focusing on soil quality rather than a unique service such as carbon sequestration. The similar linear increase in *ARC* with time in both cantons, despite different *SVI* and agricultural context, suggest that similar factors were responsible for continuous changes. In 1998, a minimum of 4 crops in the rotation, and mandatory cover crops in fall were introduced at Swiss level (Aviron et al., 2009). Later on, in both cantons farmers were growingly adopting practices such as reduced tillage, no-till, and multiple-species cover crops. Because of the particularly low *SOC* content values, incentives to apply these measures were introduced earlier in Geneva (from 1986 to 1993), which might explain the earlier increase in *ARC*. Since 2008, longer rotations, multiple-species cover crops and direct seeding have increased by 6000, 2000 and 2500 ha, respectively, in the 6500 ha of arable land of Geneva canton (N. Courtois, AgriGenève, personal communication), with dedicated subsidies allowing to foster this development. In particular the positive effect of diversified high biomass cover crops on *SOC* content and soil quality is often reported (Mary et al., 2020; O'Connell et al., 2015; Ruis and Blanco-Canqui, 2017).

The arable land topsoil *SOC* content increase potential is probably much larger than the estimated *SOC* content deficit in Fig. 4, because the 0.1 threshold is not an upper limit for Swiss arable land (Johannes et al., 2017). It can be assumed, however, that the larger the *SVI*, the more cropland soils will tend to lose *SOC*. In Fig. 9 are presented the relationships between *SVI* and *ARC* in both cantons. Indeed, there is a highly significant negative slope of *ARC* as a function of *SVI*, which tends to show that *SOC* loss is larger with large *SVI* values. However, *ARC* values larger than 10‰ are still observed for the largest *SVIs*. Further studies should, therefore, investigate the relationships between farmers practices, *ARCs* and *SVIs*, to identify these best performing cropping systems.

The MDC at field scale was discussed for Geneva canton cropland by Deluz et al., 2020. It ranged from 0.1% if best practices were applied to 0.33% when sampling errors due to former week definition of the guidelines is considered. Applying the MDC of 0.1% to the 10 year interval between two analyses allows to calculate the relationship between

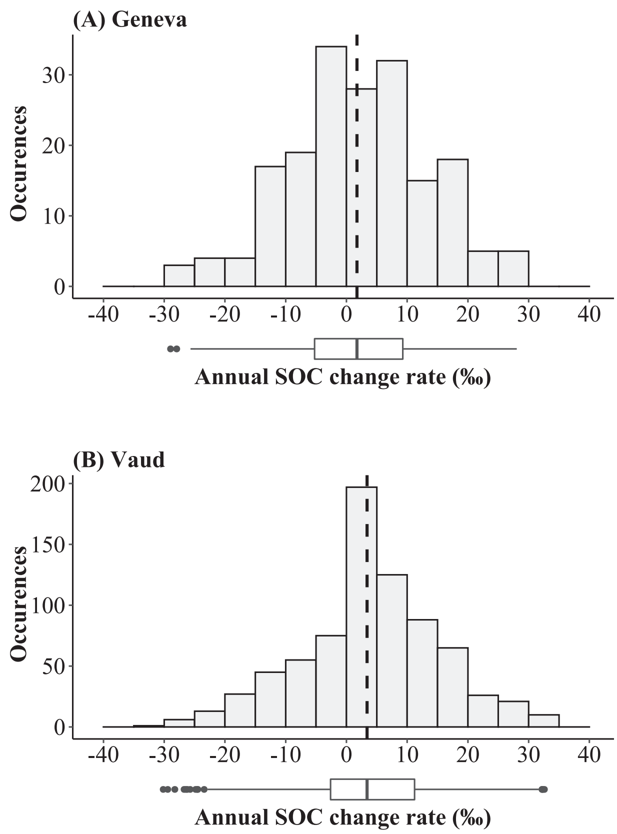

Fig. 8. Annual *SOC* content change rates *ARC* in the 0–20 cm topsoil of cropland fields from Swiss cantons of (A) Geneva (184 fields) and (B) Vaud (754 fields) over the 2007–2019 period. Dashed vertical line: median value.

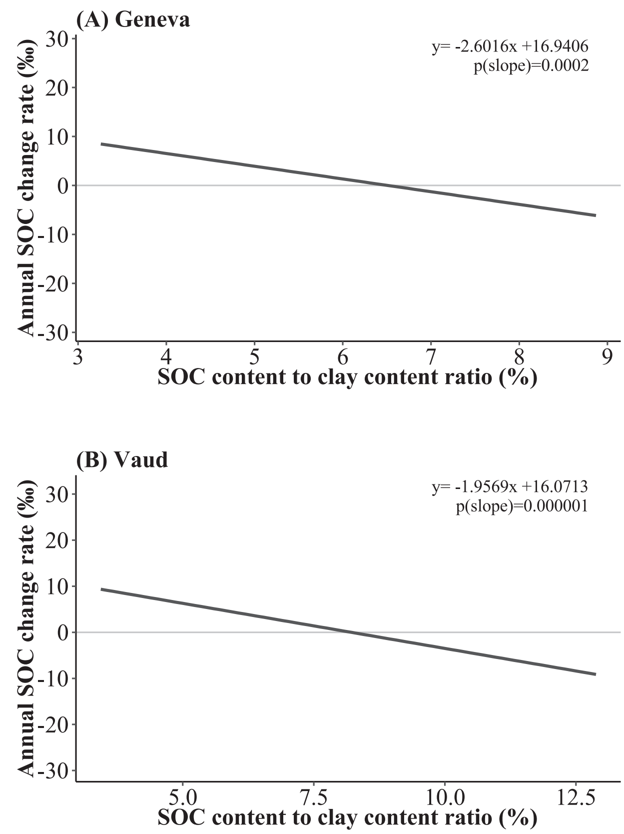

Fig. 9. Relationship between *SOC* to clay ratio and annual *SOC* content change rate in the 0–20 cm topsoil of cropland fields of (A) Geneva (165 fields) and (B) Vaud (296 fields) cantons.

ARC and the number of years before a change can be detected as a function of SOC, using Eq3. The corresponding results are presented in Fig. 10. According to this Figure, 55% of the fields show detectable *SOC* content increase or decrease after 10 years. Over a 10 year period changes in practices are most often applied, which is therefore integrated in the calculated *ARC*s. For instance, a shift from negative to positive *ARC* following improved practices may result on average in a neutral *ARC* and, therefore, non-detectable *SOC* content change in the corresponding period. Therefore, if C sequestration measures were to be generalized, the percentage of detectable *SOC* content changes over 10 years would increase with time.

The observations reported in this study are based on *SOC* gravimetric content, not *SOC* stock, which should be estimated on a larger depth, at least 30 cm according to IPCC. Moreover, changes in *SOC* stocks should be evaluated with equivalent soil mass (ESM) method (Wendt and Hauser, 2013). Conservation agriculture (CA) ("Conservation Agriculture | Food and Agriculture Organization of the United Nations," n.d.) is assumed to increase *SOC* content from the soil surface compared to conventional tillage. Oppositely, a decrease in *SOC* content below 10 to 15 cm depth and down to the plough layer under CA compared to conventional tillage was reported in many experiments (e.g., Angers and Eriksen-Hamel, 2008; Balesdent et al., 2000; Powlson et al., 2014). The *SOC* content changes reported here were assessed on the 0–20 cm layer, thus including a potential loss of *SOC* in the deeper part of this layer in the case of CA practices. CA, however, represents only 15% (Vaud) to 30% (Geneva) of the cropland area and was introduced in the past two decades, while more than 50% of the fields show positive *ARC* (Fig. 8). *SOC* turnover is slower with depth, the median depth of recent carbon incorporation into mineral soil was found at 10 cm (Balesdent et al., 2018). Therefore, differences in *SOC* content of the 20–30 cm layer of these soils on the monitoring period should be much smaller than observed on the 0–20 topsoil. This should be further assessed though past data are not available at large scale for this layer.

ESM is required because of the changes in soil specific volume (inverse of bulk density) that may occur upon changes of water content, *SOC* content and tillage. When sampling at constant depth, the changes in specific volume will result in biased *SOC* stock estimation (Wendt and Hauser, 2013). Bulk density is expected to decrease with tillage, while topsoil compaction is often expected with no-till (Balesdent et al., 2000; Wendt and Hauser, 2013). However, these effects are temporary and may reverse after 4–5 years (Pierce et al., 1994). Accordingly, an increase in bulk density upon no-tillage was not observed in the large scale survey of Johannes et al. (2017). These authors reported a unique relationship between specific volume and *SOC* content for a large number of permanent pastures, no-till and conventional tillage field samples collected at any season and any stage of the rotation. The specific volume change was mostly driven by *SOC* content, with linear relationship and R^2 as large as 70%. Therefore, changes in *SOC* content may lead to changes in soil specific volume (Boivin et al., 2009; Johannes et al., 2017; King et al., 2020; Manrique and Jones, 1991). On soils of the Swiss plateau Johannes et al. (2017), estimated the slope of the linear relationship between swollen soil specific volume and *SOC* content to 0.113. Accordingly, a +15‰ *ARC* during 10 years with 1.5% initial *SOC* content would result in a 0.24% *SOC* content increase, thus increasing the soil specific volume of 0.027 $cm^3.g^{-1}$. With a regional average value of 0.7 $cm^3.g^{-1}$, this represents a volume increase of less than 4%. Assuming isotropic volume change, this would represent a 1.3% layer thickness change, corresponding to a 0.26 cm increase of the

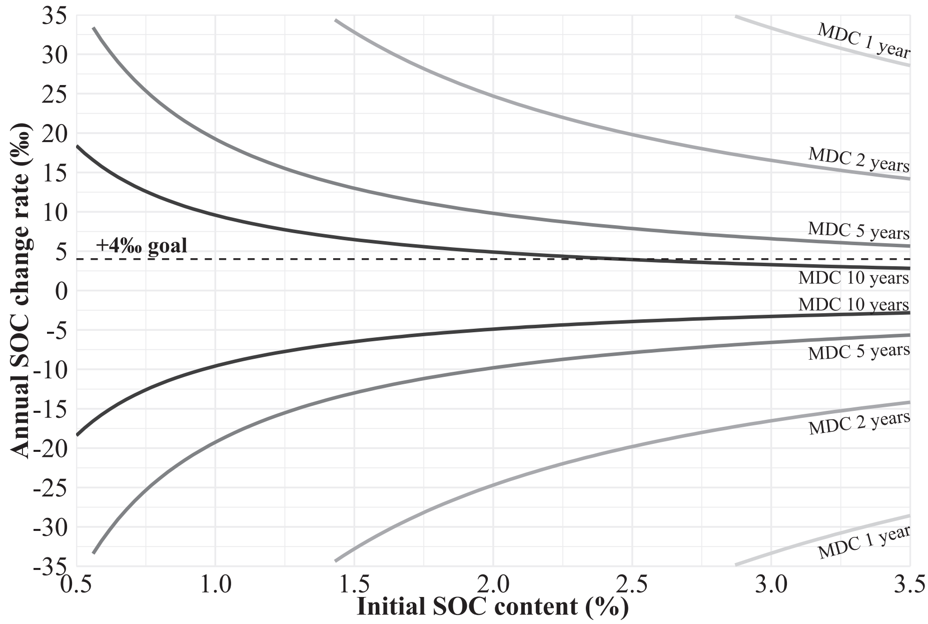

Fig. 10. Number of years before a change is detectable at field scale, as a function of SOC content and annual change rate in *SOC* content. Dots are observed change rates, solid lines are detectability limits, into brackets are the % of observations included in the detectability limit.

0–20 cm layer thickness. Moreover, soils are swelling with water, which results in rapid changes of their bulk density. For instance, on the studied soils swelling capacities of 5% of the volume were reported with less than 20% clay content, while increasing *SOC* content limited soil swelling (Boivin et al., 2009). While the effects of no-till and *SOC* content increase may oppose, moisture content at sampling can be considered as random on large numbers. Therefore, considering the large number of fields in this study and the equilibrium between positive and negative *ARCs*, we assume that the bulk densities may not be systematically biased towards larger or smaller values from a sampling date to the next one in our data set. If so, C stocks in the 0–20 cm layer may follow on average the same patterns as *SOC* content changes, i.e. same *ARC* distribution and time trend, which should be further confirmed.

5. Conclusions

The *SVI* threshold of 0.1 was used to determine a minimum *SOC* deficit in cultivated soils. In the 20 cm topsoil of western Switzerland cropland, the deficit is large, up to 70% of increase in *SOC* content is required in Geneva cropland to reach an acceptable structure vulnerability, which is much more demanding than the 4‰ climate target.

The range of observed annual rates of change in *SOC* from 1993 to present were very large, from −30‰ to +30‰ with median value equal to 0. However, the time trends showed a highly significant linear increase, from negative (-4‰) in 1998 to average annual rates of change above the 4 per 1000 goal. Neutrality was reached by 2005–2007, and present average was larger than +5‰. Because the trends were very close despite the many differences between the two cantons, we suspect that the main factors are related to the Swiss agri-environmental schemes applied at the end of 20th century, namely mandatory cover corps and minimum rotations of 4 crops. Further *SOC* increase is accordant with the continuing adoption of minimum tillage, conservation agriculture and diversified intense cover crops. The average patterns observed with *SOC* content may be similar in average with carbon stocks due to the large number of field analyses used. These findings oppose those obtained in Swiss Long-Term Experiments and plea to use on-farm information when adressing issues such as agriculture policy, climate mitigation, and soil quality management.

Declaration of Competing Interest

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

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