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Soil-climate factors have a greater influence on the presence of winter cover crops than regulatory constraints in France

Benjamin Nowak¹ · Audrey Michaud² · Gaëlle Marliac³

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Abstract

Despite the benefits associated with winter soil cover before sowing a spring crop, this practice is adopted unevenly by farmers. The goal of this paper is to identify and hierarchize the main soil-climate factors that hinder the adoption of cover crops. It is the first study to carry out this analysis at the scale of France, which is a country with a wide variety of soil types and climates. For this country, maps of vegetated winter soil cover prior to the establishment of a spring crop were previously produced for years 2018 and 2019, using Sentinel-2 multispectral images. For approximately half of France's acreage with spring crops, the estimation concerning the presence or absence of a winter cover crop was correlated here with the main soil-climate factors of each field. The inclusion within Nitrate Vulnerable Zones is another potentially important variable to explain cover crop adoption, as regulatory requirements of the Nitrates Directives strongly encourage winter soil cover in these zones to reduce nitrogen losses. Because of the regulatory requirements of the Nitrates Directives regarding winter soil cover, the influence of being located in a Nitrate Vulnerable Zone was also evaluated. But despite these incentives for winter soil cover, inclusion in a Nitrate Vulnerable Zone had little influence on cover crop adoption. Principal component analyses performed for different crop rotations showed that the clay content was the soil-climate factor most negatively correlated with the adoption of cover crops. Cover crops were more frequently established on sandy fields with high organic carbon stocks, which corresponds rather to the characteristics of livestock regions. The development of technical solutions for the establishment and destruction of winter cover crops on clay soils could facilitate the adoption of these crops, and thus improve global water quality.

Keywords Cover crop · Nitrate · Soil cover

1 Introduction

The main benefits of winter cover crops before sowing spring crops are largely recognized. Recent works show that cover cropping increases soil microbial abundance, activity, and diversity (Kim et al. 2020). Winter soil cover slows down surface runoff, thus limiting erosion (Dabney et al. 2001) while nutrient uptake by plants reduces losses due to leaching when soils are saturated with water (Decrem et al. 2007). In

particular, nitrate losses to natural ecosystems are associated with extensive environmental damage such as water eutrophication or decline in drinking water quality. To reduce this pollution, the European Union introduced the Nitrates Directive in 1991 (91/676/EC). Within the framework of this directive, Nitrate Vulnerable Zones are defined throughout Europe when nitrate levels exceed critical thresholds (i.e., 50 mg/L for surface freshwater). In these zones, appropriate agricultural practices must be implemented to limit nitrate losses, including winter soil cover.

Despite the benefits associated with winter soil cover and the regulatory requirements of the Nitrates Directives, the adoption of cover crops is commonly considered to be low to moderate (USDA 2021). Using multispectral imagery (Fig. 1), winter soil cover rate before spring crops was estimated between one-third and one-half of French fields, with strong spatial variability (Nowak et al. 2021). As a comparison, Nitrate Vulnerable Zones cover 68% of the country's agricultural area (Programme d'actions national nitrates 2020).

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Many factors influence the adoption of cover crops, from social issues such as available labor (Lee and McCann 2019) or farmers' perception of this practice (Mallory et al. 1998) to physical features. Regarding the influence of soil-climate conditions, low rainfall limits the amount of water available for cover crops in dry climates (Tribouillois et al. 2018). Besides, the water used by cover crops can negatively impact yields of following cash crops (Dabney et al. 2001). In colder climates, the low sum of growing degree days limits cover crop growth, especially after spring crops that will be harvested later than winter crops (Pullens et al. 2021). In the Netherlands, it has been shown that a hot and dry summer led to earlier harvest dates, hence earlier sowing dates for cover crops and greater development of these crops (Fan et al. 2020). Little research has addressed more specifically the relationship between soil characteristics and the adoption of cover crops but Seifert et al. (2018) highlighted that farmers are more likely to adopt the practice on fields with poor soil quality, where the benefits associated with cover crops are most strongly needed.

The main objective of this study is to disentangle the effect of climate and soil characteristics on the adoption of winter cover crops, taking into account the regulatory constraints related to the Nitrates Directive that apply to some territories. This work was conducted for France, which has a wide variety of soil types and climates.

2 Materials and methods

This study focuses on all fields with spring crops in France, declared within the context of the European Common Agricultural Policy (about 99% of the French arable crop

area). These fields are mapped in a file known as the "Registre Parcellaire Graphique" in France. In this file, a field corresponds to an area cultivated with one main crop (or a crop mixture) in a given year. Spring crops are cultivated on about 5 million hectares each year, with 90% of this acreage taken up by only four crops (maize, sunflower, barley, and sugarbeet). Two years of cultivation have been taken into account for the study: 2018 and 2019 harvests.

2.1 Estimation of winter soil cover through Sentinel-2 multispectral images

For France, maps of vegetated winter soil cover prior to the establishment of a spring crop were previously produced for years 2018 and 2019 (Nowak et al. 2021). For each year, vegetation monitoring was carried out for two months (December and January) during the winter before sowing the spring crop. For this period, soil cover was estimated through the computation of the Normalized Difference Vegetation Index (NDVI) for each field, using Sentinel-2 multispectral images at 10 m resolution. A 20 m negative buffer was applied to the borders of each field to avoid edge effects due to sensor resolution or ground geolocation uncertainty.

The spatial average NDVI of each field that will be sown with a spring crop at the end of the winter was calculated for each satellite acquisition date that was available over the study period. The final value retained for each field corresponds to the maximum NDVI value among all average NDVI values calculated for the December–January period. Following this protocol, part of the fields could not be monitored because of topological error in the original shapefile delimiting the plots or no cloud-free pixel for the period considered (33% and 16%

Fig. 1 Vegetated winter soil cover with a mustard cover crop (Marmilhat, France. Photograph by the authors). Such soil coverage is easily detected on multispectral satellite images by computing vegetation indices such as the Normalized Difference Vegetation Index (NDVI). For the NDVI calculated from these images, a threshold of 0.52 can be considered as corresponding roughly to a 50% soil coverage by vegetation (Nowak et al. 2021). For comparison, bare soils are generally characterized by NDVI values of about 0.2.



of France's acreage under spring crops without NDVI extraction in 2018 and 2019, respectively). Additional information about the NDVI extraction procedure can be found in the study by Nowak et al. (2021).

2.2 Definition of previous crop

The field register from the previous year was used to evaluate the effect of the previous crop but this association could only be carried out for part of the plots because the borders of some of them were modified from one year to the next. Approximately half of France's acreage had both winter NDVI value and previous crop information (41% in 2018 and 53% in 2019).

2.3 Soil features

Data on soil features used in this study are from the SoilGrids project, which combines soil observations, remote sensing, and machine learning to create digital soil maps at 250 m resolution (Hengl et al. 2017). Among SoilGrids available observations, the features considered here are soil texture (clay, silt, and sand content), organic carbon stocks, and pH. For all these features, the values considered in this study refer to the horizon from 0 to 30 cm depth. Similar to NDVI computation, the value retained for each soil feature is the spatial average for each field.

2.4 Terrain features

Elevation comes from NASA Shuttle Radar Topography Mission digital elevation model (Farr et al. 2007). The resolution of this dataset is 0.0003°, which corresponds approximately to a grid of 33 m (latitude) by 21 m (longitude) for France (Table 1). Two additional features were calculated from elevation: slope and aspect. Similar to NDVI computation, the value retained for each terrain feature is the spatial average for each field.

2.5 Climate data

Mean air temperature at 2 m and sums of precipitation were extracted from the ERA5 dataset (Copernicus Climate Change Service 2017). The resolution of this dataset is 0.25°, which corresponds approximately to a grid of 28 km (latitude) by 19 km (longitude) for France. Because of this resolution, and as the climatic conditions can be considered relatively homogeneous on small territories, the climate data were averaged at the municipality scale (each field in a given municipality shares the same climate data). The average size of municipalities in metropolitan France is 14.9 km² (Dumont 2014).

In order to include the sowing period of cover crops as well as the most favorable periods for the development of those crops, for each given year, 5 months of data prior to establishment of spring crops were considered: from August to December 2017 (for the 2018 harvest) and from August to December 2018 (for the 2019 harvest).

2.6 Nitrate vulnerable zones

Besides soil and climate variables, the inclusion within Nitrate Vulnerable Zones is another potentially important variable to explain cover crop adoption as regulatory requirements of the Nitrates Directives strongly encourage winter soil cover in these zones to reduce nitrogen losses. For each field, the inclusion in a vulnerable zone was determined at the municipality level (Sandre 2021).

2.7 Data processing

Previous work showed that crop rotation has a strong impact on winter soil cover rate (Nowak et al. 2021). To minimize this influence, here it was decided to focus on a limited number of crop sequences for most of the data analysis. Regarding the previous crop, two types of crops have been distinguished: winter crops and spring crops (Fig. 2). Temporary grassland included in crop rotations is excluded from the analysis because, due to their late date of destruction; they can provide

Table 1 Main sources of the data.

Data source	Features	Resolution
Sentinel-2 multispectral images	Normalized Difference Vegetation Index (NDVI) to monitor soil cover by vegetation	10 m × 10 m
SoilGrids digital soil maps	Soil characteristics (clay, silt, and sand content, pH and organic carbon stocks)	250 m × 250 m
Shuttle Radar Topography Mission digital elevation model	Elevation, slope, and aspect	Approximately 33 m × 21 m
ERA5 global climate and weather dataset	Mean air temperature at 2 m and sums of precipitations for end of summer (August and September) and fall (October, November, and December) before sowing spring-sown crops	Approximately 28 km × 19 km

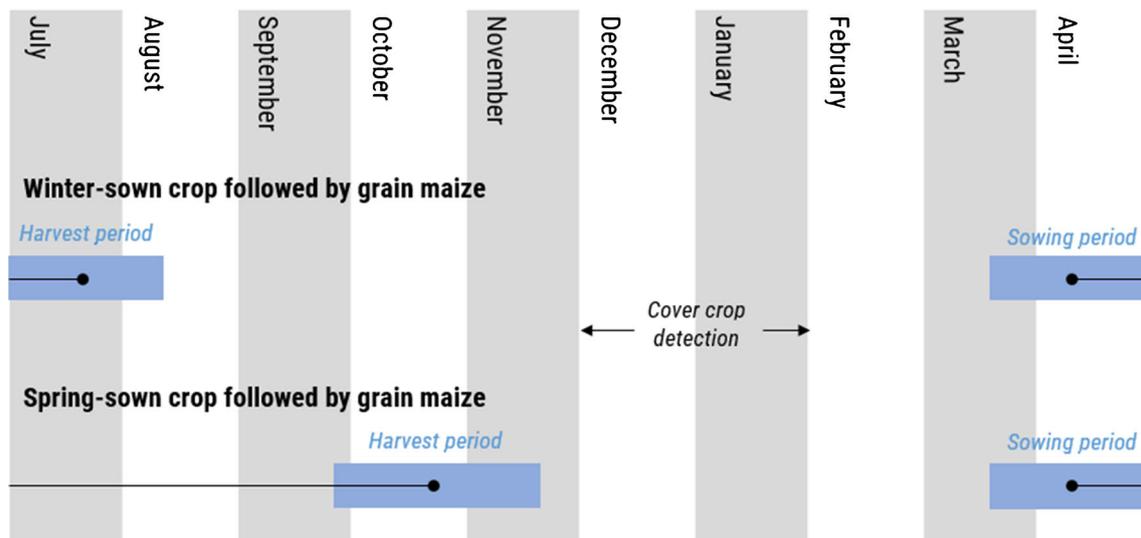


Fig. 2 Timeline of the two crop sequences analyzed in this study.

winter soil cover unrelated to cover crop establishment. Regarding the next crop, special attention has been given to grain maize, because it is the main spring crop grown in France (about one third of the total acreage under spring crops). Thus two crop sequences of cultures have been defined; winter crop (e.g., winter soft wheat) followed by grain maize and spring crop (e.g., grain maize) followed by grain maize. These two crop sequences accounted for 142,262 fields (616,079 ha) and 228,950 fields (760,667 ha) respectively. The fields were distributed fairly evenly between the two study years. The median size of the fields selected for this study was 2.31 ha (with a first quartile of 1.23 ha and a third quartile of 4.53 ha).

The relationship between soil cover rate and the explanatory variables detailed above was first studied by performing a principal component analysis (PCA) for both crop sequences. PCA was used to classify the plots according to these variables and then winter NDVI (considered as a proxy for winter soil cover) was added as an additional variable to investigate the relationships between the different features and the probability of adoption of cover crops. Finally, the influence of the different variables on winter soil cover has been studied separately. Data extraction was realized through the Google Earth Engine platform (Gorelick et al. 2017). Analysis was conducted in R (R Development Core Team 2009) and figures were produced using the ggplot2 package (Wickham 2016).

3 Results and discussion

3.1 Ranking of factors' influence on winter soil cover

Principal component analyses were performed for the two selected crop sequences (winter crop followed by grain maize

and spring crop followed by grain maize) in order to compare the relative influence of the different factors on winter soil cover (Fig. 3, Table 2). For both crop sequences, the first two axes of the principal component analyses explained approximately 42% of the variation in field variables. As shown on Table 2, the first axis was mainly defined by soil features such as pH (correlation coefficient of -0.53 for both crop sequences), clay content (-0.35 for winter crop followed by grain maize and -0.40 for spring crop followed by grain maize), and organic carbon stocks (0.48 and 0.34).

For both crop sequences, winter soil cover was mainly related to the first axis, with correlation coefficients between this axis and the additional variable winter NDVI of 0.51 for winter crop followed by grain maize and 0.39 for spring crop followed by grain maize. Considering a threshold of NDVI of 0.52 for a covered soil, the discrimination between covered and uncovered fields according to the first axis can also be seen on the graph of individuals (Fig. 3).

Furthermore, these plots show higher winter NDVI values (i.e., higher soil cover) for the fields with the crop sequence winter crop followed by grain maize. This is most likely due to an earlier harvest leaving more time for cover crop sowing and growth.

Among the different factors evaluated, the influence of soil features on winter soil cover was the most obvious. Also, this influence was similar for both crop sequences. The plots of variables show that soils with high clay content and high pH are usually associated with low winter NDVI (i.e., low vegetated winter soil cover), whereas soils with high sand content and high carbon organic stocks are associated with high probability of winter soil cover, with both soil features pointing in the same direction as the winter NDVI (Fig. 3).

The decorrelation between clay content and organic carbon stocks observed here may seem surprising, since interaction

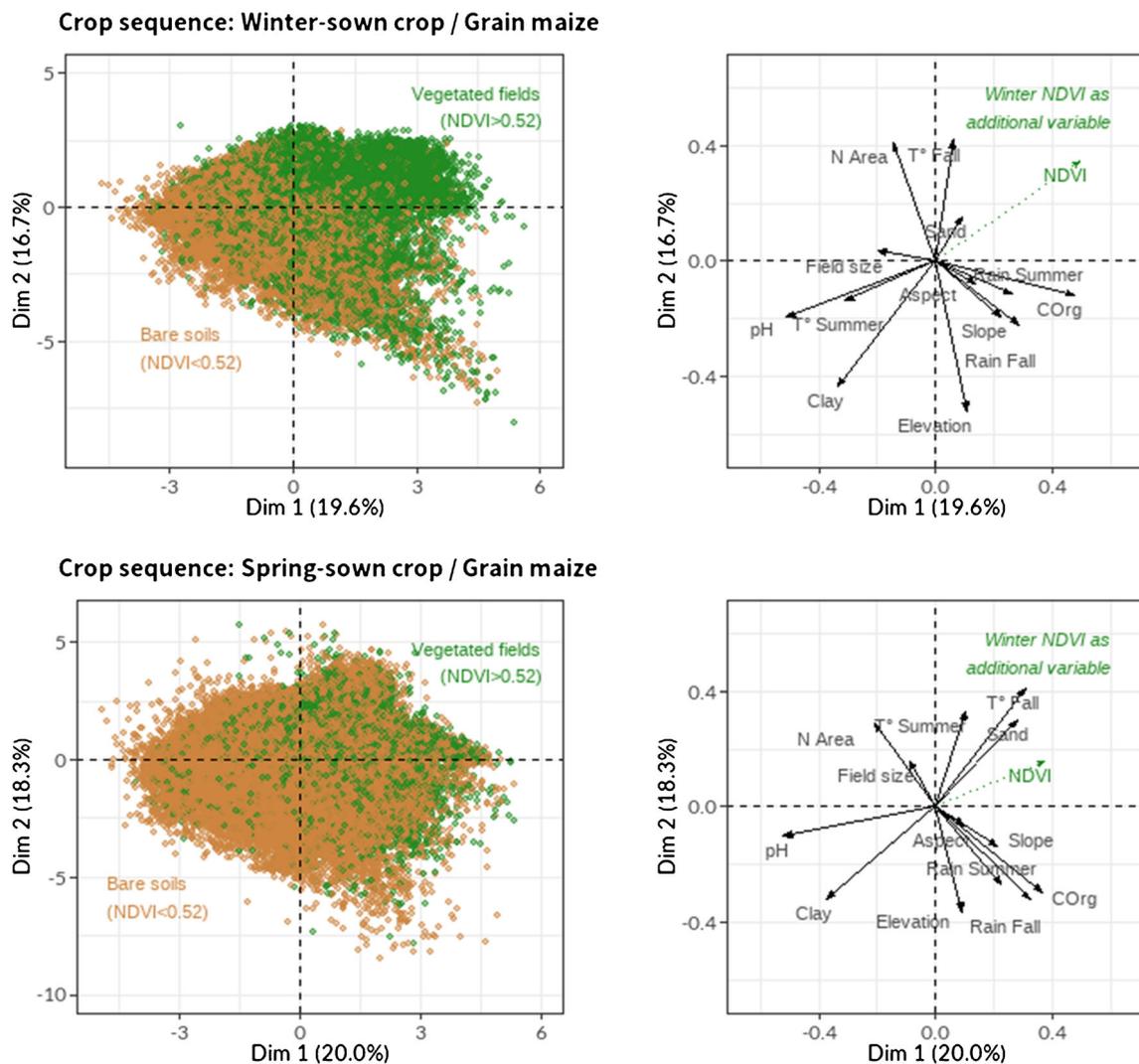


Fig. 3 Plots of individuals (left) and variables (right) with the first two axes of principal component analyses performed for the two crop sequences: grain maize preceded by winter crop (top) and grain maize preceded by spring crop (bottom). NDVI refers to the Normalized

Difference Vegetation Index and COrg refers to the organic carbon stocks from 0 to 30 cm depth. For the sake of clarity, only a random selection of one-quarter of the fields have been represented on plots of individuals, each point corresponding to one field.

with clay is regarded as one the most important mechanisms to explain soil organic matter stabilization (Wiesmeier et al. 2019) and several studies previously highlighted strong correlation of soil organic carbon stocks with clay content (Hassink 1997; Arrouays et al. 2006). But it has also already been mentioned that the segregation between crop and livestock may cause a mismatch between potential soil organic carbon storage capacities and current stocks, as crops tend to be cultivated on soils with high clay content, but with little organic inputs, such as manure (Nowak 2021). The results of the principal component analyses would indicate that cover crops are more frequently established on sandy fields with high organic carbon stocks, which in France corresponds rather to the characteristics of livestock regions. This is consistent with the winter soil cover map of the country (Fig. 4), which shows a higher cover ratio in areas specialized in livestock productions

(such as Brittany in the West of France) and a lower ratio in areas specialized in crop productions (such as the Paris basin in the center of the country).

For livestock systems, cover crops adoption is a way to produce additional fodder resources (Singer et al. 2007; Arbuckle and Roesch-McNally 2015), whereas the lack of market opportunities hinders the adoption of these crops for arable farms (Roesch-McNally et al. 2018). Moreover, the timing of cover crop sowing often coincides with other critical field activities such as cash crop harvest and sowing. Therefore, despite farmers' positive perceptions about cover crops, these crops may be dismissed because of their overall negative impact on the farm as a whole (Plastina et al. 2020).

Regarding the effect of climate variables, the influence of temperature seems more important than that of rainfall. Contrasting with soil features, the influence of temperature

Table 2 Correlation of the variables with the first two principal components (PC1 and PC2) of the principal component analyses (PCA).

PCA variables			Crop sequence			
Type of features	Short name (on PCA)	Description	Winter wheat/Grain maize		Grain maize/Grain maize	
			PC1	PC2	PC1	PC2
Soil	Clay	Clay content from 0 to 30 cm depth	-0.34	-0.43	-0.37	-0.32
	Sand	Sand content from 0 to 30 cm depth	0.09	0.15	0.28	0.30
	Corg	Organic carbon stocks from 0 to 30 cm depth	0.48	-0.12	0.37	-0.32
	pH	Soil pH from 0 to 30 cm depth	-0.51	-0.19	-0.52	-0.10
Terrain	Field size	Field size	-0.20	0.03	-0.09	0.16
	Elevation	Field elevation	0.10	-0.51	0.09	-0.36
	Slope	Field slope	0.22	-0.19	0.21	-0.13
	Aspect	Exposure (0 for North exposure, 90 for East exposure and so on)	0.14	-0.08	0.09	-0.06
Climate	Rain Summer	Rainfall during summer months relevant to this study (August and September)	0.26	-0.11	0.20	-0.26
	Rain Fall	Rainfall during fall months (October, November and December)	0.29	-0.22	0.32	-0.32
	T° Summer	Temperature during summer months relevant to this study (August and September)	-0.31	-0.14	0.10	0.33
	T° Fall	Temperature during fall months (October, November and December)	0.06	0.42	0.31	0.41
Nitrate Vulnerable Zones	N Area	Binary variable (0 for field outside, 1 for fields within Nitrate Vulnerable Zones)	-0.15	0.41	-0.21	0.29
Vegetation index	NDVI	Maximum Normalized Difference Vegetation Index value during the winter before sowing next spring crop	0.51	0.33	0.39	0.13

varies with crop sequences. Winter soil cover appears negatively correlated with late summer temperature (i.e., temperatures for August and September) for fields with winter crop as previous crop; whereas it is positively correlated with fall temperature (i.e., temperatures for October, November, and December) for fields with spring crop as previous crop. Such a result is consistent with the key requirements for cover crops: avoid excessive stressful summer temperatures after a winter crop and get high enough growing degree days sums during the fall after a summer crop.

More surprisingly, inclusion in a Nitrate Vulnerable Zone seemed to have only moderate influence on winter NDVI for the crop sequence with winter crop as previous crop and no influence for the crop sequence with spring crops as previous crop (the two variables being almost perpendicular on the plot). The conclusions of the PCA regarding this point are further supported by the French soil cover map (Fig. 4), which does not show a clear trend related to Nitrate Vulnerable Zones.

Such a result can be partially explained by the derogations allowed by the Nitrates Directive. In France, the main measures of the action programs of the Nitrates Directive are adapted at the regional scale in order to be consistent with local conditions. In this context, winter soil cover is often

not required if the previous crop is a spring crop. For example, in the case of the Auvergne-Rhône-Alpes region, winter soil cover is not mandatory if the previous crop was harvested after the first of October (Préfet de la région AURA 2018). Other possible exemptions will be discussed in the following paragraphs.

For both crop sequences, elevation, aspect, and slope have little influence on winter soil cover. This being said, altitude is negatively correlated to NDVI, while slope is positively correlated to winter soil cover. The latter may be explained by the benefit of soil cover to limit water run-off and soil erosion during periods of heavy rainfall. Furthermore, the fact that mountainous areas, with steep slopes and high altitudes, are rarely classified as Nitrate Vulnerable Zones (Fig. 4) could explain the weak correlation between slope and adoption of cover crops, despite the interest of these crops in these areas.

3.2 Influence of soil features

Principal component analyses showed that soil characteristics, particularly soil texture, had the greatest influence on winter soil cover. Figure 5 shows the relationship between soil texture alone and winter NDVI for the two crop sequences considered. In both cases, Loess regressions

showed that winter soil cover is negatively correlated with the clay content of the fields.

Seifert et al. (2018) already highlighted that farmers are more likely to grow cover crops on sandy fields, with low potential, and hypothesized that this adoption was done for the purpose of soil improvement. It can also be assumed that the low adoption rate of cover crops on clay fields is due to the tillage constraints related to those plots. In particular, clay soils have a higher water retention capacity, thus limiting the possibility of destruction of cover crops during the winter. These constraints are taken into account by the Nitrates Directive. For the Auvergne-Rhône-Alpes region, if the clay content is higher than 30%, winter soil cover is not mandatory, even if the previous crop is a winter crop (Préfet de la région AURA 2018).

However, it is not possible to demonstrate such threshold effects with the data used in this study. Figure 5 shows a relatively low diversity of soil textures in the SoilGrids data (e.g., from 10 to 54% of clay in this dataset). Moreover, several comparisons of these data with field measurements have already been conducted, particularly in France (Tifafi et al. 2018; Lemerrier et al. 2021). For the Alsace region, it was shown that, although SoilGrids digital maps reflected the major trends of the territory, their accuracy was not sufficient to work at finer scales. For the case of the study presented here, at the scale of France, it was therefore considered that the data used allowed the comparison of soil types in a relative way, but are not precise enough to determine absolute values (e.g., what level of clay is a critical barrier to the establishment of intermediate crops?). Further work will be required to determine these critical values

3.3 Influence of climate

Figure 6 shows the relationship between climate data and winter NDVI. Compared to Figure 3, the results are reported here by month, and not by season (in Fig. 3, summer corresponds to August and September, while fall corresponds to October, November, and December).

As already mentioned above, climatic factors had less influence than soil factors on the adoption rate of cover crops. In fact, the distribution curves of climatic factors for fields with vegetated cover or bare soils overlap largely. For example, the mean October temperature does not appear to influence winter soil cover for the crop sequence winter-sown crop followed by grain maize. This is consistent with the results of principal component analyses (Fig. 3) which showed that soil characteristics had more influence on winter soil cover than climate data.

However, some trends can be observed in Fig. 6. For the crop sequence winter-sown crop followed by grain maize, the development of cover crops seems to be favored by oceanic climates (i.e., cooler summers and warmer falls), rather than

continental climates with more contrasted seasons. Such a finding is consistent with the map shown in Fig. 4, which indicates a higher adoption of cover crops on the Atlantic coast. The negative correlation between end of summer mean temperature and adoption of cover crops may be explained by high heat stress conditions for successful cover crop establishment.

For the crop sequence spring-sown crop followed by grain maize, the same trend is found for fall temperatures, while late summer temperatures do not seem to influence the development of cover crops. Thus, contrary to what has been observed in the Netherlands by Fan et al. (2020), it seems that earlier harvest dates of previous spring crops do not encourage farmers to establish more cover crops. The most decisive months were the one that generally correspond to the establishment of cover crops, with a positive correlation between monthly mean temperature and soil cover for the following winter. This could be explained by higher sum of growing degree days supporting the development of cover crops.

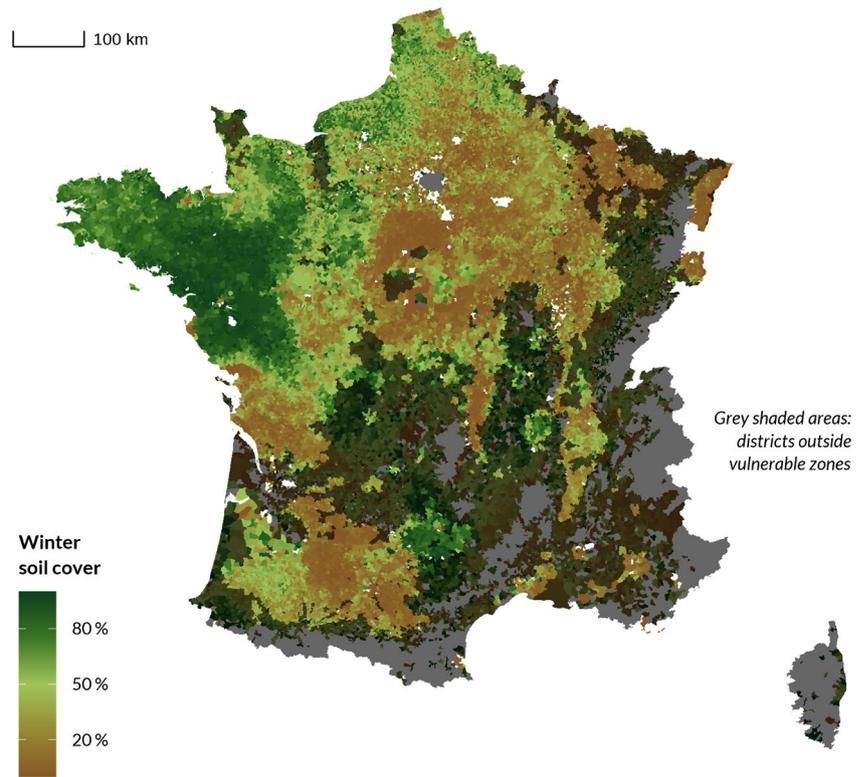
The influence of rainfall was less obvious than the influence of temperature for both crop sequences. However, this study may underestimate the effect of rainfall. Access to irrigation, which is not taken into account here, can lift water stress for some fields. Moreover, the spatial resolution of the ERA5 global climate and weather dataset is less precise than the other datasets that are used in this study (Table 1). If this dataset allows to highlight the main climatic trends on a national scale (as shown with the diversity of situations illustrated in Fig. 6), some local heterogeneities can be neglected.

While a global rise in temperature is predicted with climate change, several studies have already investigated the consequences of this rise for the evolution of crop yields or diseases in France (Gammans et al. 2017; Caubel et al. 2017). Regarding the evolution of winter soil cover before spring crops, climate change could modify the distribution of cover crops, which are currently mainly established after the harvest of winter crops. With increasing temperatures, sowing of cover crops after the harvest of winter crops could decrease because of climate conditions that are too stressful during the summer while this evolution could favor the development of cover crops in the fall, after the harvest of spring crops.

3.4 Winter soil cover in Nitrate Vulnerable Zones

Figure 4 shows the average winter soil cover before spring crops by municipality. This map indicates a high spatial variability of winter soil cover within the country. Despite the regulatory requirements of the Nitrates Directives for winter soil cover, this variability does not seem to be related to the classification as Nitrate Vulnerable Zones: municipalities classified as Vulnerable Zones have a winter soil cover rate above 80% in the West, whereas this rate is less than 20% for the

Fig. 4 Winter soil cover rates before spring crops (all spring crops combined) aggregated at the municipal level for years 2018 and 2019. A field is considered as covered if the Normalized Difference Vegetation Index (NDVI) exceeds the threshold of 0.52 during the winter.



municipalities in center of France. Such a finding shows that derogations concerning the establishment of winter cover are frequent in some areas of the country. In contrast to agri-environmental schemes, compliance with Nitrate Vulnerable Zones regulations often involves substantial investment costs for the farmer (Franklin et al. 2021). In particular, the establishment of cover crops can be seen as a constraint rather than a benefit. This may have negative consequences on the achievement of the objectives of the Nitrates Directive.

In France, the Nitrate Vulnerable Zones have been extended by successive classifications. However, further analysis performed for this study showed that the date of classification had little influence on the winter soil cover rate. For example, Brittany, in the west of France, and the Paris basin, in the center, are among the first classified areas but now show very different winter soil cover rates (Fig. 4). To explain this, the strong pressure due to unfavorable public opinions might have speed up the changes in agricultural practices in Brittany.

Crop sequence: Winter-sown crop / Grain maize

Crop sequence: Spring-sown crop / Grain maize

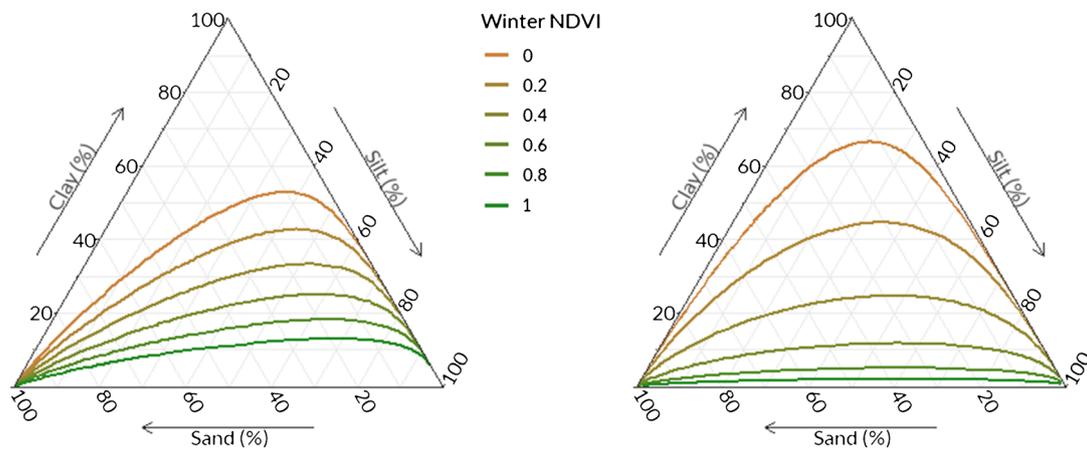


Fig. 5 Relationship between soil texture and winter soil cover (estimated by Normalized Difference Vegetation Index (NDVI)). Lines show the results of Loess regressions conducted on all the fields.

Doubts were expressed early on about the possibilities of achieving the objectives of the Nitrates Directive (Worrall et al. 2009). For France, the assessment of the implementation of the Nitrates Directive for the period from 2016 to 2019 showed an overall stable state of the water bodies compared to the previous campaign (Ministère de la transition écologique 2020). Yet, this stability hides contrasted trends within the country. The North and East of France show a general upward trend, while the West (the Brittany region) appears to be improving. These trends seem to be partially correlated to the winter soil cover highlighted in Fig. 4. In particular, the Brittany region shows the highest winter soil cover, with more than 80% of soil cover before spring crops.

Thus, understanding the barriers limiting the adoption of winter cover crops and developing effective solutions could improve water quality.

4 Conclusion

This study is the first to compare the effect of soil-climate factors and regulatory constraints on the adoption of cover crops in France. It has been shown here that, despite the regulatory requirements of the Nitrates Directives regarding winter soil cover, inclusion in a Nitrate Vulnerable Zone had little influence on cover

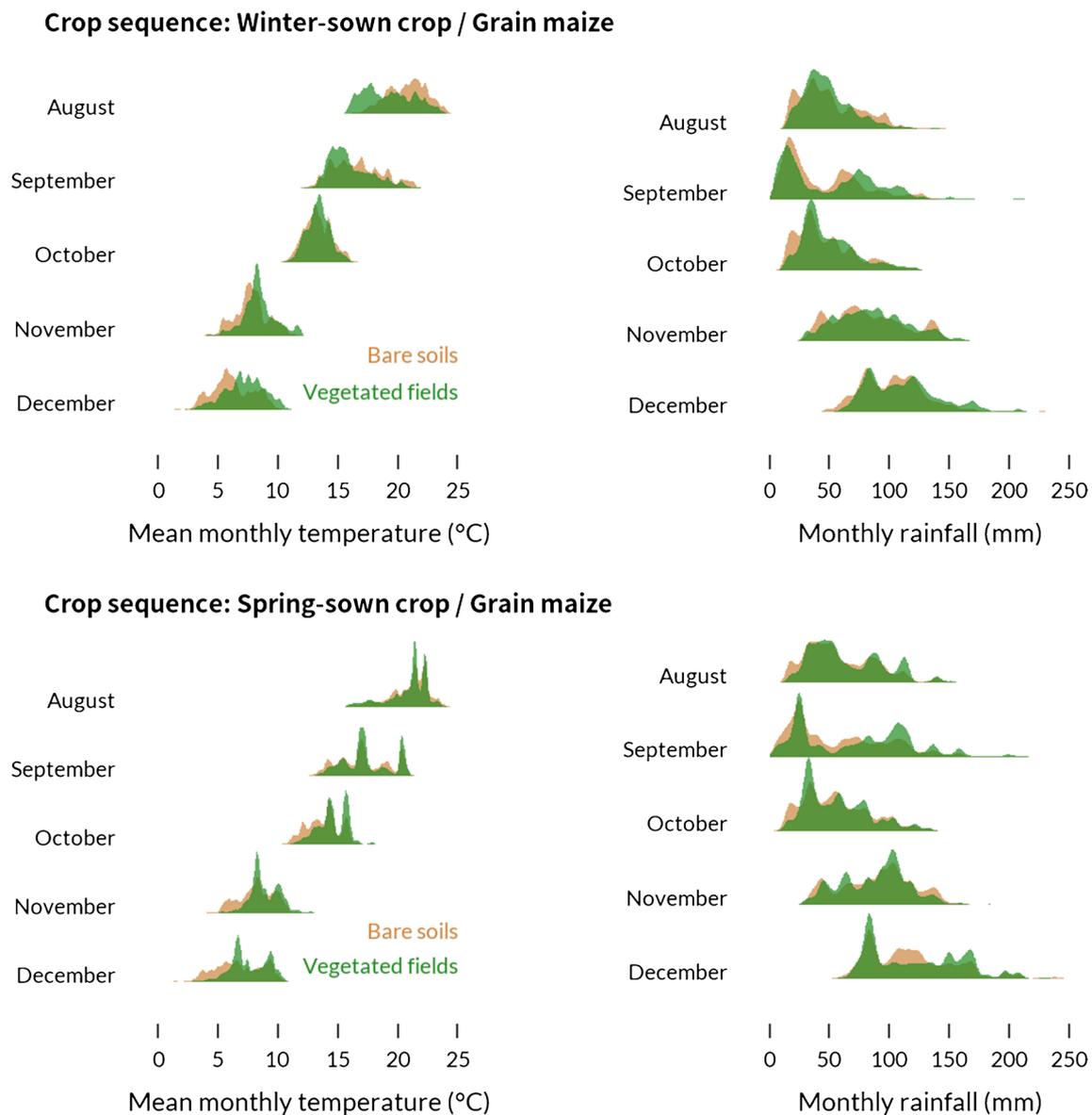


Fig. 6 Comparison of distribution curves of summer (August and September) and fall (October, November, and December) temperatures (left) and rainfalls (right) for two types of fields (fields with winter soil

cover and those with bare soil) and for two crop sequences: grain maize preceded by winter crop (top) and grain maize preceded by spring crop (bottom).

crop adoption. This could hinder the achievement of the Nitrates Directive objectives, as areas that show an improvement in water quality are also those that have the highest winter soil cover ratio. While a very high variability in winter soil cover rate before spring crops has been observed within the country, this study showed that clay content was the soil-climate factor most negatively correlated with the adoption of cover crops. This result could be partially explained by an indirect effect, with clay soils being more frequently associated with arable farms. Cover crops were more frequently established on sandy fields with high organic carbon stocks, which corresponds rather to the characteristics of livestock regions. For arable farms, the lack of market opportunities hinders cover crop adoption. But it can also be assumed that there is a direct effect between clay content and the non-adoption of winter cover crops as tillage is more complicated in wet conditions on heavy, clay-rich soils. These constraints are acknowledged by the Nitrates Directive, which offers potential exemption for winter soil cover above a given clay content. The development of technical solutions for the establishment and destruction of winter cover crops on clay soils could facilitate the adoption of these crops, and thus improve global water quality.

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Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Benjamin Nowak. The first draft of the manuscript was written by Benjamin Nowak and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data that support the findings of this study are available upon reasonable request from the authors.

Code availability The code for data cleaning and analysis associated with the current study is available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interests The authors declare no conflict of interest.

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