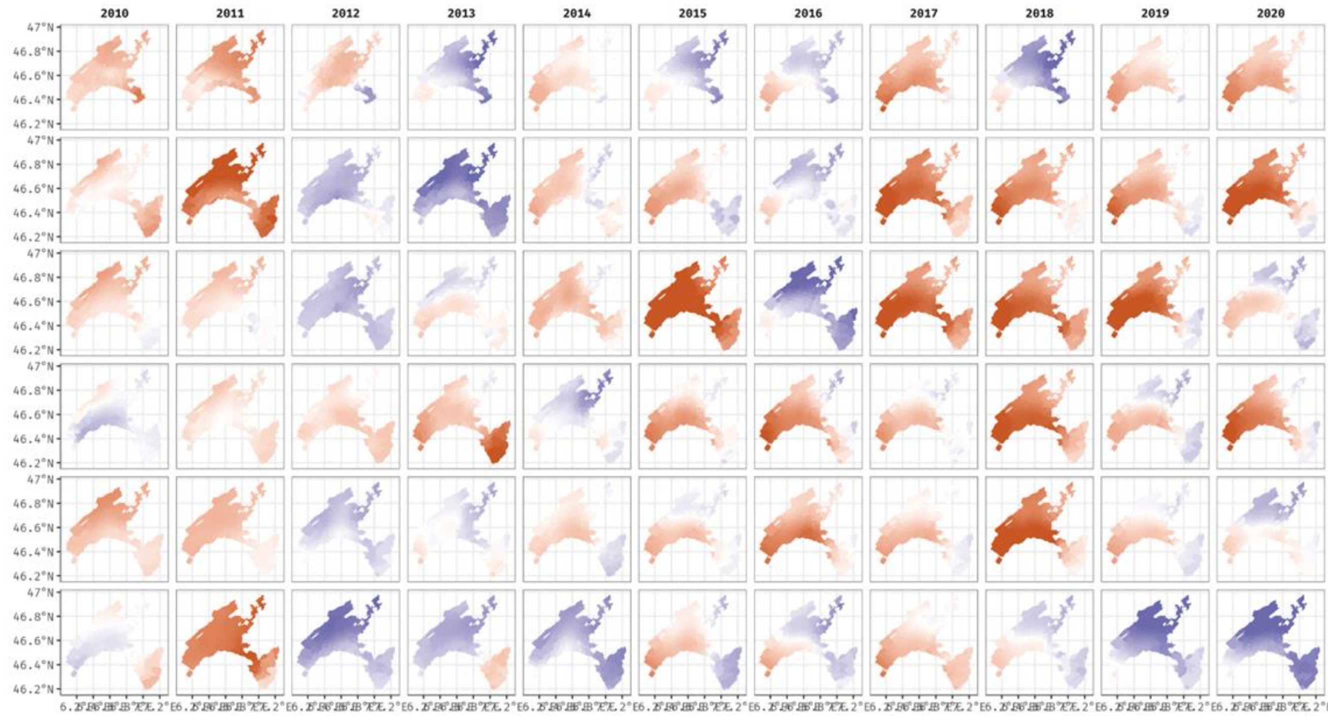
Study on historical soil moisture level in the canton of Vaud



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List of Abbreviations

AV 2040	**Agriculture Vaudoise 2040**
BAMS	**Bulletin of the American Meteorological Society**
EAA	**Economic Accounts for Agriculture**
ESA	**European Space Agency**
FOAG	**Federal Office for Agriculture**
FSO	**Federal Statistical Office**
IPCC	**Intergovernmental Panel on Climate Change**
JAXA	**Japan Aerospace Exploration Agency**
LPRM	**Land Parameter Retrieval Model**
NASA	**National Aeronautics and Space Administration**
NCCS	**National Center for Climate Services**
NDVI	**Normalized Difference Vegetation Index**
PA 22+	**Politique Agricole 2022+**
REAA	**Regional Accounts for Agriculture**
UAA	**Utilised Agricultural Area**

Proconseil
Une filiale de Prométerre

VanderSat

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Executive Summary

Prométerre had the will to better understand the historical soil moisture change, and its potential impact on agriculture production for the canton of Vaud. As part of this project, Prométerre asked VanderSat, a provider of satellite-observed data specialized in passive microwaves, to conduct an analysis of the soil moisture trend for the last 40 years in canton of Vaud. Compared to precipitation, soil moisture measures directly the water available to plants. Although precipitation is key in the definition of a meteorological drought, soil moisture is an excellent indicator of the edaphic drought or « agricultural drought[1] ».

For this analysis, a dataset of daily soil moisture values at municipalities level was used. Soil moisture anomalies were derived by comparing the daily value to the climate normal 1981 – 2010 (long-term average of the former World Meteorological Organisation reference period for describing the current climate). The soil moisture anomalies were standardized and accumulated for six periods (1.5 months long) during the growing season of each year (from 15th of march to 15th of december). A potential trend was then assessed by using a linear regression for each municipality.

Overall, the results demonstrate that the soil moisture deficits increase and the soil moisture excesses decrease, except for the end of the autumn where an increase of soil moisture excesses seems to occure. During the growing period, the increase of the soil moisture deficit is stronger at the end of spring and beginning of summer. This lack of water at these times of the year might affect both winter and summer crops, while soil moisture excess in late autumn would rather impact winter crops. In terms of trend, there are only minor variations between the different municipalities. In other words, the whole canton is following a similar trend.
Further, the climate normals 1981- 2010 show an absolute soil moisture level higher in early spring compared to later in the season. Therefore, the crops might be exposed to higher soil moisture level because they develop earlier as a consequence of the temperature increase. This situation would possibly jeopardize their growth even thought an increase of the soil moisture excess is not measured for this time of the year.

This study suggests that over time, farmers are coping with increasing challenges, both in terms of soil moisture deficits (end of spring and beginning of summer) and soil moisture excesses (end of autumn), but also because the crops might develop earlier (higher temperature) and suffer from wetter conditions (early spring).
Finally, the satellite data indicate that the evolution of the soil moisture content over the past 40 years follows the same trend for the entire canton of Vaud. Consequently, the adaptation measures to climate changes must be chosen based on the regional capabilities to adapt their production systems rather on climatic trends themselves.

Keywords:
Soil moisture
Satellite data
Climate
Canton of Vaud

[1] INRAE (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement), 2020. Qu'est ce que la sécheresse. INRAE, accessed on 23.12.2021, https://www.inrae.fr/actualites/quest-ce-que-secheresse.

Résumé

Prométerre a eu la volonté de mieux comprendre l'évolution de l'humidité des sols dans le passé, et son impact éventuel sur la production agricole du canton de Vaud. Dans le cadre de ce projet, Prométerre a demandé à VanderSat, fournisseur de données satellites spécialisé dans les micro-ondes passives, de réaliser une analyse de l'humidité du sol des 40 dernières années dans le canton de Vaud. Par rapport aux précipitations, l'humidité du sol mesure directement l'eau disponible pour les plantes. Alors que les précipitations sont essentielles dans la définition d'une sécheresse météorologique, l'humidité du sol est un excellent indicateur de la sécheresse édaphique ou « sécheresse agricole[2]».

Pour cette analyse, une base de données de valeurs d'humidité dans le sol a été utilisée à l'échelle de la commune. Les anomalies d'humidité dans le sol ont été calculées en comparant les valeurs quotidiennes à la norme climatique 1981-2010 (moyenne à long terme de l'ancienne période de référence de l'organisation météorologique mondiale pour décrire le climat actuel). Puis les anomalies d'humidité du sol ont été standardisées et accumulées pour six périodes (d'une durée de 1,5 mois) au cours de la saison de croissance, et ceci pour chaque année (du 15 mars au 15 décembre). Une tendance potentielle a ensuite été évaluée à l'aide d'une régression linéaire pour chaque commune.

Dans l'ensemble, les résultats mettent en évidence que les déficits hydriques du sol augmentent et que les excès d'humidité du sol diminuent, sauf pour la fin de l'automne où une augmentation des excès d'humidité du sol est observée. Pendant la période de croissance, l'augmentation du déficit hydrique du sol est plus forte à la fin du printemps et au début de l'été. Ce manque d'eau au cours de ces périodes pourrait affecter les cultures d'hiver et d'été, tandis que l'excès d'humidité du sol en fin d'automne impacterait plutôt les cultures d'hiver. En termes de tendance, les fluctuations entre les communes sont mineures. Autrement dit, tout le canton suit une tendance similaire.
De plus, les normes climatiques 1981-2010 indiquent un niveau absolu d'humidité du sol plus élevé au début du printemps. Par conséquent, les cultures peuvent être exposées à un niveau d'humidité du sol plus élevé car elles se développent plus tôt en raison de l'augmentation de la température. Cette situation pourrait compromettre leur croissance même si une augmentation de l'excès d'humidité du sol n'est pas mesurée pour cette période de l'année.

Cette étude suggère, qu'au cours du temps, les agriculteurs font face à des défis croissants, à la fois en termes de déficits et d'excès d'humidité du sol, mais aussi parce que les cultures peuvent être plus précoses (température plus élevée) et souffrir de conditions plus humides (début du printemps).
Enfin, les données satellites indiquent que l'évolution de la teneur en humidité du sol au cours des 40 dernières années suit la même tendance pour tout le canton de Vaud. Par conséquent, les mesures d'adaptation aux changements climatiques doivent être choisies en fonction des capacités régionales à adapter leurs systèmes de production plutôt que des tendances climatiques elles-mêmes.

Mots clés:
Humidité du sol
Données satellites
Climat
Canton de Vaud

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[2] INRAE (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement), 2020. Qu'est ce que la sécheresse. INRAE, accessed on 23.12.2021, https://www.inrae.fr/actualites/quest-ce-que-secheresse.

1. Introduction

1.1. Prometerre and AV 2040

Prométerre is an association for the promotion of agricultural professions in the canton of Vaud, Switzerland. It brings together and defends the interests of the agricultural organizations and farms of the canton of Vaud by participating in the definition of the framework conditions for agriculture. Moreover, through its three mains departments: Insurance, professional promotion and services & advices; Prométerre supplies a wide range of services to its members. It also maintains regular contacts with the political world and the administration. These fruitful collaborations enable it to have a good understanding of the current agricultural environment and to promote a common policy for its members and others agricultural organizations.

Throught the implementation of the Regional Agricultural Strategies, key pillar of the new agricultural policy PA22+, Prométerre was planning to develop the part dedicated to the agricultural infrastructures and markets in the project called “Agriculture Vaudoise 2040” (AV 2040). This project aimed to find the optimal conditions for a productive agriculture by defining the future strategies to adapt to climate changes and to answer to market expectations and needs. By applying policies tools, the objective of AV 2040 was to focus on the improvement of agricultural infrastructures as well as the development of production, processing and marketing structures of agricultural products.

As part of the « water balance regulation » component of the project, Prométerre mandated VanderSat to study the soil moisture change (water deficits and excesses) over the last 40 years (1981 – 2020). Indeed, Prometerre fosters the use of new technologies and believes that satellites images analyses can spur innovation in agriculture and, especially, in the field of water management.

1.2. VanderSat

VanderSat is a scientific company based in Harlem (Netherlands) and is known as a leading provider of global satellite-observed data, products and services. VanderSat monitors and analyses the land conditions. Its data were inputs for the Intergovernmental Panel on Climate Changes (IPCC), the Bulletin of the American Meteorological Society (BAMS), state of the climate report and the European Space Agency (ESA) climate change initiative.

In short, VanderSat gives to his customers essential insights into soil and crop conditions by applying their mathematical expertise to raw data from a constellation of satellites from several space agencies including the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA).

Based on satellites data, VanderSat is able to provide different services, such as

- Precision farming advice : Irrigation module and pesticide application ;
- Crop yield prediction improvement ;
- Index insurance independant calculation agent : drought index and soil moisture excess index ;
- Credit risk score improvement for loans ;
- Water and fire management.

Regarding the soil moisture data, VanderSat uses the data from the following satellites: SMAP and GPM (NASA), AMSR-2 & AMSR-E (JAXA) and SMOS & Sentinels (ESA).

1.3. Scope of the project

This project was a joint project between Proconseil and VanderSat. VanderSat had the objective to analyse its historical soil moisture dataset to study the evolution of soil moisture level (deficits and excesses) over the last 40 years in canton of Vaud. While the duty of Proconseil consisted to gather reliable yield data for selected crops.
The overall aim of the project was to have the big picture of the soil water content change for the last 40 years and the effect on agricultural production in order to define the strategy for the canton of Vaud in terms of water management and climate change adaptation.

More specifically, the purposes of the project were to:
- Assess the soil moisture over the last 40 years in the canton of Vaud ;
- Determine a trend in soil moisture deficits and excesses in the canton of Vaud ;
- Investigate the correlation of soil moisture indicators (excess and deficit) with the yields (t/ha) of selected crops depending on the first results;
- Create some visuals (maps and graphs) for the AV 2040 project communication.

The project will focus on the historical soil moisture data for the area of the canton of Vaud over the last 40 years. VanderSat will provide data at the municipalities level (« 308 communes ») and at the canton level.
In terms of timing, the contract has been signed on the 5th of February 2021, and the outcome of the study was presented in the form of a presentation on the 18th of May 2021. Afterwards, the report has been written and finalised on the 5th of May 2022.

2. VanderSat data

2.1. Background

It is important to specify that compared to rainfall data (precipitation), soil moisture data is a key parameter to assess water available to plants. It is an excellent indicator of edaphic drought or agricultural drought as it does take in account water runoff, soil texture, evaporation, ground water contribution... Soil moisture is water directly available to the plant.

VanderSat uses passive microwave technology to offer highly accurate measurements of soil water content and crop status, unhindered by cloud cover or darkness in contrast to the Normalized Difference Vegetation Index (NDVI) satellites data. Indeed, this signal is not hindered by atmospheric conditions or darkness, providing a very consistent and regular record.
The natural emissions in the microwave domain (X, C and L bands) are measured by satellites in what is called the “Brightness Temperature”. The natural emissions do not contain a lot of energy and the satellite sensors only collect the information with a low resolution (large footprint, resolution: 25 km * 25 km).
VanderSat downscales this signal by using a patented algorithm, a Gaussian disaggregation method (DIFSAT; US Pat. # 10,643,098, EU Patent # 17 728 899.0), which allows to retrieve high resolution brightness temperatures (resolution: 100m * 100m).
Then, VanderSat applies the Land Parameter Retrieval Model (LPRM) to the passive microwave observations in order to obtain daily high-resolution soil moisture data. The LPRM is based on a radiative transfer model and determines the soil and the vegetation contribution to the observed brightness temperatures according the equation[3],[4] (1):

$$(1)\quad T_b = (e\, T_s)\, \Gamma + (1-\omega) T_C\, (1-\Gamma) + (1-e)\,(1-\omega)\, T_C\, (1-\Gamma)\, \Gamma$$

T_b: Observed brightness temperatures
T_s: Thermometric temperatures of the soil
Γ: Transmissivity
ω: Single scattering albedo
T_C: Thermometric temperatures of the canopy
e: Rough surface emissivity

Throught this model it is possible to retrieve two key land parameters:
- The surface soil moisture and ;
- The vegetation optical depth (proxy data of the vegetation water content).

The soil moisture is measured by retrieving the parameter e (soil emissivity) directly related to the dielectric constant. The dielectric constant represents the « mobility » of water in the soil and is related to soil moisture by taking in account the soil texture. The satellite soil moisture

[3] Owe M, De Jeu R, Walker JP (2001). A Methodology for Surface Soil Moisture and Vegetation Optical Depth Retrieval Using the Microwave Polarization Difference Index. IEEE Transactions on Geoscience and Remote Sensing, 39, 1643-1654.
[4] de Jeu R, Holmes T, Parinussa R, Owe M (2014). A spatially coherent global soil moisture product with improved temporal resolution. Journal of Hydrology, 516, 284-296.

information is expressed as volumetric soil moisture in m^3/m^3. It represents the soil moisture of the first 5 to 10 cm of the soil[5].
Depending on the periods studied, VanderSat treats its remotely sensed passive microwave dataset as follow:

- Prior 2002 : ERA5-Land reanalysis data, volumetric soil water layer 1 ;
- Since 2002: use of L band radiometer from the SMAP satellite of NASA and C band radiometer from the AMSR-E and AMSR-2 satellite of JAXA.

The final time series are obtained by calculating a 20-day moving average of the daily observation. The calculation of an average of soil moisture over a 20-day period allows to retrieve a smoother signal that reflect better the condition in the root-zone[6] (~ 50 cm).
VanderSat evaluated its soil moisture data against ground observation (sensors), others satellite products and models in Europe, United States, and United Kingdoms. Overall, the results show a good correlation and validate VanderSat products[7,8].

2.2. Soil moisture data visualisation

As an example, the figure 1 pictures the soil moisture express in m^3/m^3 on the 10th July 2015 compared to the 10th July 2020. The red color depicts dry condition with a soil moisture content closer to zero, while blue would indicate a wetter condition and the yellowish an intermediate situation. In one sight, it appears clearly that the 10th July 2015 was a drier day than the 10th July 2020. Everybody, and especially the farmers, would agree that the summer 2015 was very hot and dry and that agriculture suffered from a drought…

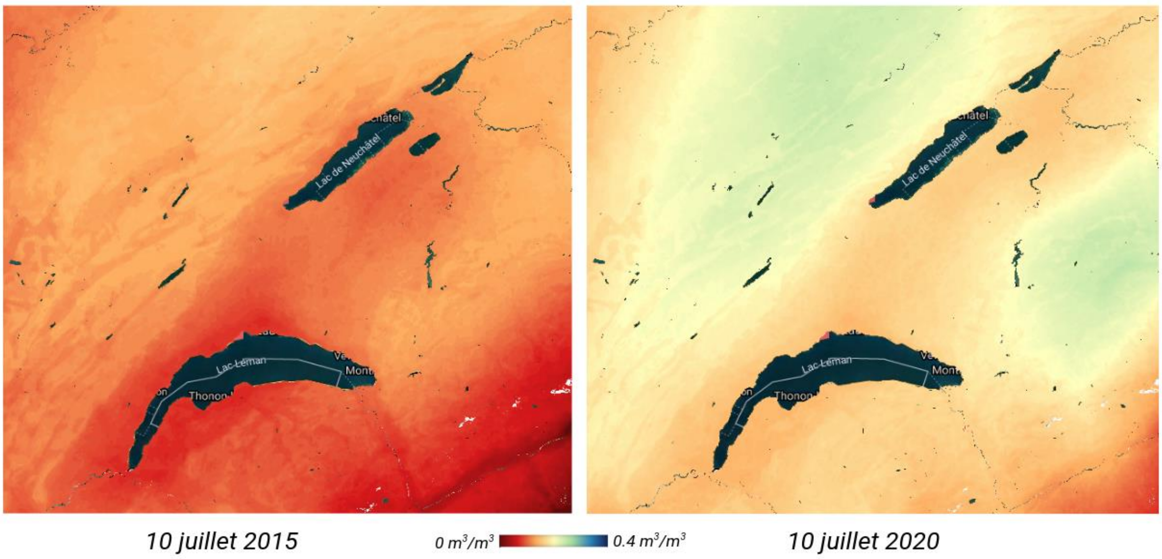

Figure 1: Soil moisture measurements [m^3/m^3] in canton of Vaud.

[5] Njoku E & Entekhabi D (1996). Passive microwave remote sensing of soil moisture. Journal of Hydrology, 184, 101-129.
[6] Albergel C, Rüdiger C, Pellarin T, Calvet JC, Fritz N, Froissard F, Suquia D, Petitpa A, Piguet B, Martin E (2008). From near-surface to root-zone soil moisture using an exponential filter : an assessment of the method based on in-situ observations and model simulations. Hydrol. Earth Syst. Sci., 12, 1323-1337.
[7] van der Schalie R, Parinussa R, Renzullo L, van Dijk A, Su C, de Jeu R (2015). SMOS soil moisture retrievals using the land parameter retrieval model: Evaluation over the Murrumbidgee Catchment, southeast Australia. Remote Sensing of Environment, 163, 70-79.
[8] de Jeu R & de Nijs A (2017). Evaluation of high resolution satellite soil moisture products using a dense network of groundwater level observations. Stromingen, 28 (2).

3. Methods

3.1. Description

In this study, the climate normals from the period 1981-2010 are used and not the recent updated period 1991-2020. As described previously (Chapter 2.1), the daily soil moisture data are calculated and the final time series are obtained (20-day moving average) based on daily satellite images for each municipality, from 1981 to 2020. Then, the climate normal (1981-2010) is determined for each municipality as being the daily soil moisture averages from 1981 to 2010 (Figure 2). The differences from these averages express the positive and negative anomalies, namely the soil moisture excesses and the soil moisture deficits, respectively in blue and orange in the figure 3.
In order to take in account the standard deviation of the anomalies, positive and negative Z-scores are calculated following the equation (2) (Figure 4):

$$(2)\ Z = \frac{x - \mu}{\sigma}$$

Z= Z-score
X= Daily anomaly
μ= Average of the daily anomalies (~ 0)
σ= Standard deviation of the anomalies

Thus, one value of Z-score is obtained per day for each municipality, over the 40 years.

Subsequently, each year is divided into 6 periods of 1.5 months in order to assess soil moisture during the growing season (Figure 5):

- Start of spring: 15^{th} March - 30^{th} of April
- End of spring: 1^{st} of May - 15^{th} of June
- Start of summer: 16^{th} of June - 31^{st} of July
- End of summer: 1^{st} of August - 15^{th} of September
- Start of autumn: 16^{th} of September - 31^{st} of October
- End of autumn: 1^{st} of November -15^{th} December

Therefore, the deficit and the excess indexes are computed by accumulating the positive Z-scores and the absolute values of the negative Z-scores to evaluate the soil moisture for each defined period from 1981 to 2020 (Figure 6, case of the deficit indexes). The next step is to decrease the interannual variability due to weather (and not because of climate change), by calculating a 5-year moving average to both indexes (Figure 7, case of the deficit indexes).
Finally, a linear regression model is applied on those accumulated Z-scores to identify potential trends (Figure 8, case of the deficit indexes; see chapter 3.2 stastical analysis).

To summarize, the following steps were used to prepare and analyse the data for each municipality over 40 years (1981 - 2020):

1. Estimation of the daily soil moisture data;
2. Calculation of the time series (extraction and alignment);
3. Computation of the daily climate normals (1981-2010) (Figure 2);
4. Determination of the daily positive and negative anomalies (Figure 3);
5. Computation of the Z-scores: standardization of the daily negative and positive anomalies (Figure 4);
6. Division of the year into 6 periods of 1.5 months (Figure 5);
7. Determination of the soil moisture indexes per period (Deficit and excess indexes) (Figure 6);
8. Calculation of a 5-year moving average of the indexes (Figure 7);
9. Identification of potential trends by using a linear regression model on the soil moisture indexes (Figure 8).

3.2. Statistical Analysis

- Data exploration, normality, independance of observations, and homoscedasticity:

Statistical analysis was conducted with the software R, version 4.0.4 (Lost Library Book). The data have been plotted and visualized.
Within each municipalilty and period of the year, the year-to-year realisations of the index are assumed to be independent (but this was not verified). Further, the realisations of the index are assumed to be normally distributed, even though it could not be verified due to the limited number of observations. The same is also true for homoscedasticity.

- Description of the trend:

A simple linear regression (ordinary least square linear regression) was used to describe a potential trend in the indices (deficits and excess indices) over the last 40 years. This analysis was repeated for each municipality and periods of the year (growing season).

The regression line has the following equation: $Y= a + b X$
Y = deficit or excess index (accumulated anomalies)
X = years
b= slope of the regression line
a= intercept

The slope (b) identifies the direction and the intensity of the trend. The coefficient of determination R^2 indicates which share of the index variability can be explain by the independent variable, in our case by the variable “year”.
In this model, the null hypothesis H0 proposes that there is no trend in the realisation of the accumulated anomalies in the last 40 years (H0= the slope of the linear regression is 0). The alternate hypothesis H1 says that there is a trend (two-sided, increasing or decreasing trend) in the realisation of the accumulated anomalies over time.

The p-value measures the probability that the null hypothesis is true or not. When the p-value < 0.05, then the null hypothesis is rejected and it is concluded that there is a trend at a significance level $\alpha=0.05$ (there is only a 5% chance that the observed trend is random).

3.3. Soil moisture and yields data correlation

Through this study, it was also intentended to correlate soil moisture indexes with the yield of some selected crops to study the impact of water excesses and droughts on agricultural production in canton of Vaud. On that purpose, Proconseil, as the technical subsidiary of Prométerre, had the tasks to determine priority crops, to collect yields of these crops over the past 40 years, and to document the other factors determining the variation in yields (economic, ecological, political, etc.).

In parallel with the historical soil moisture level analysis, the objective was to obtain consistent yield time series for selected crops.

3.4. Case of Orbe municipality

In this chapter, the steps 3 to 9 of the method are pictured with a focus on soil moisture deficits analysis for the municipality of Orbe. The same visualisation for the soil moisture excesses is available in the annex 1.

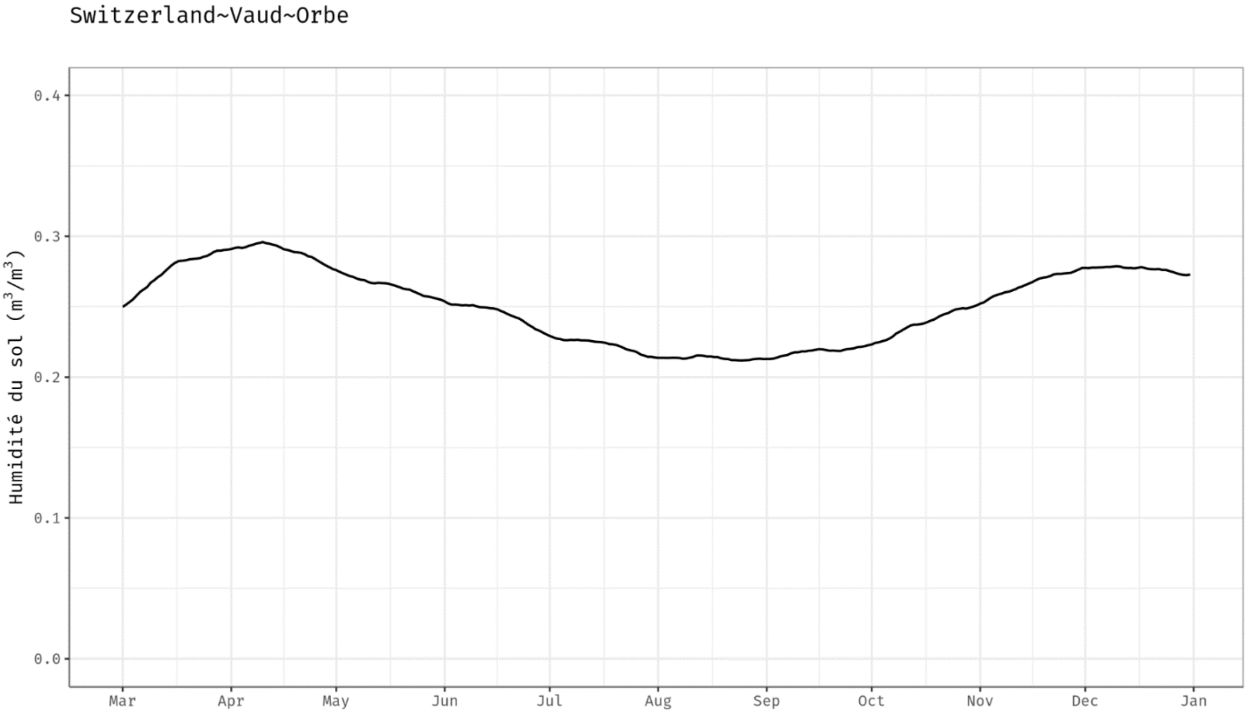

Figure 2: Climate normal for the municipality of Orbe, 1981-2010 (Step 3).

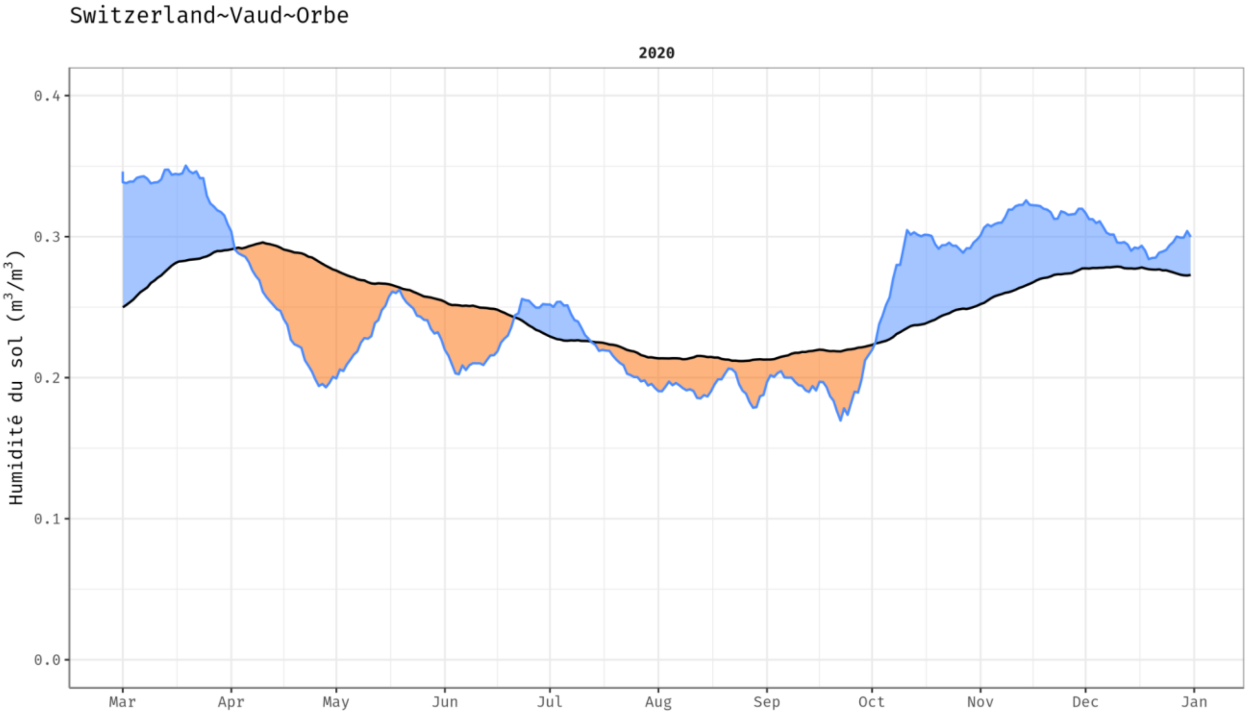

Figure 3: Positive and negative daily anomalies, Orbe, 2020 (Step 4).

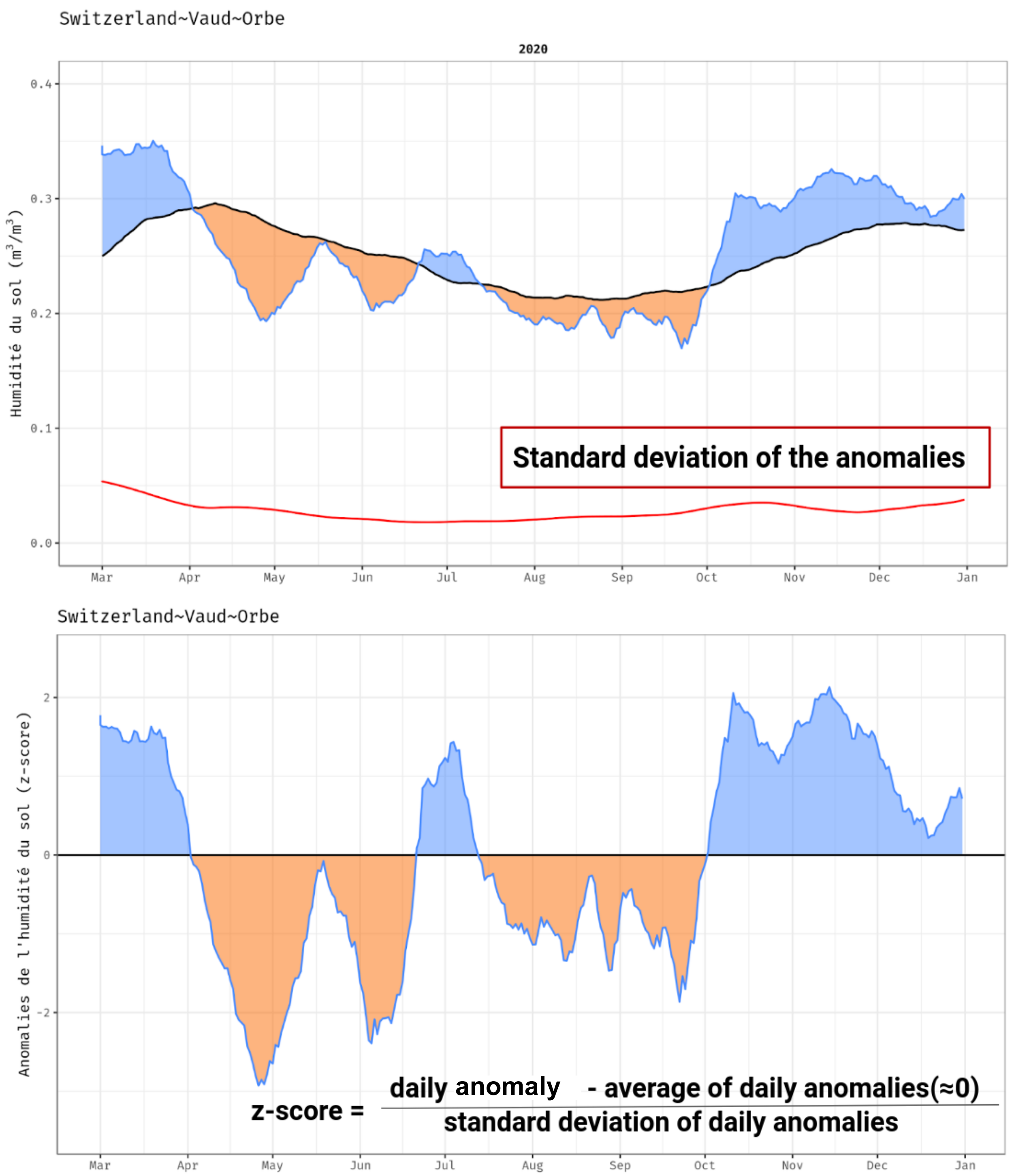

Figure 4: Standardization of the anomalies by using Z-score, Orbe, 2020 (Step 5).

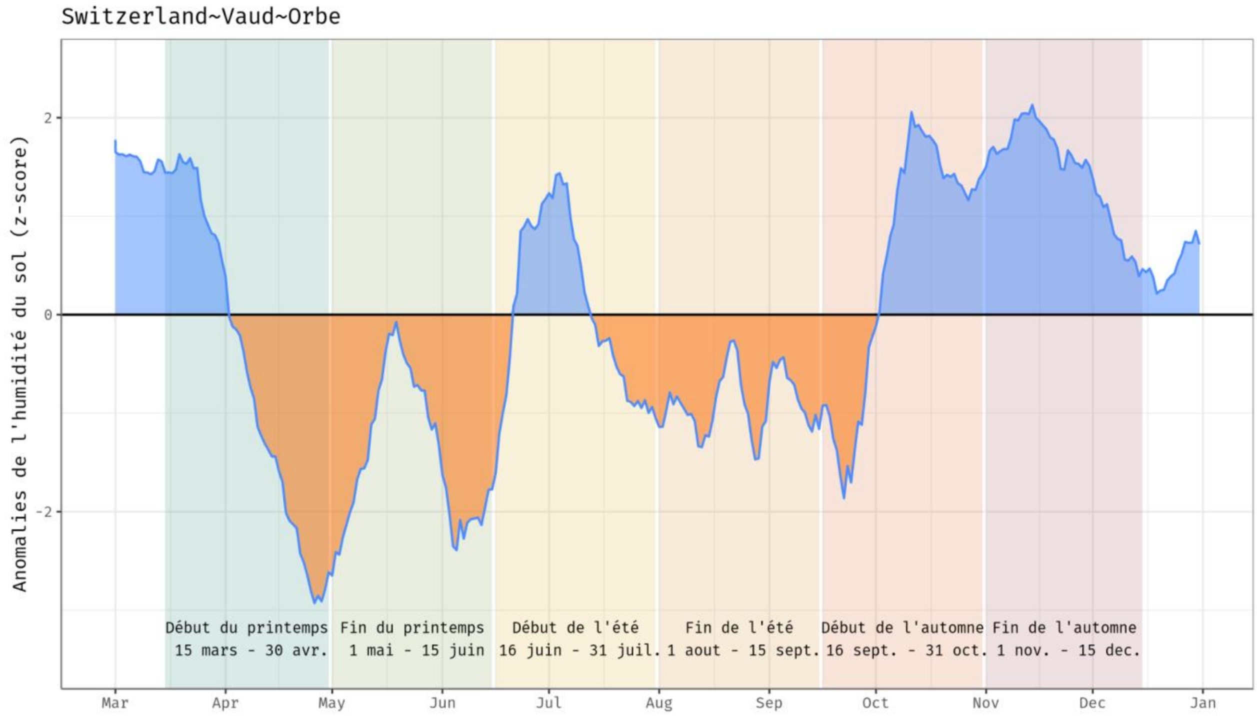

Figure 5: Soil moisture anomalies standardized (=Z-scores), 6 periods defined, Orbe, 2020 (Step 6).

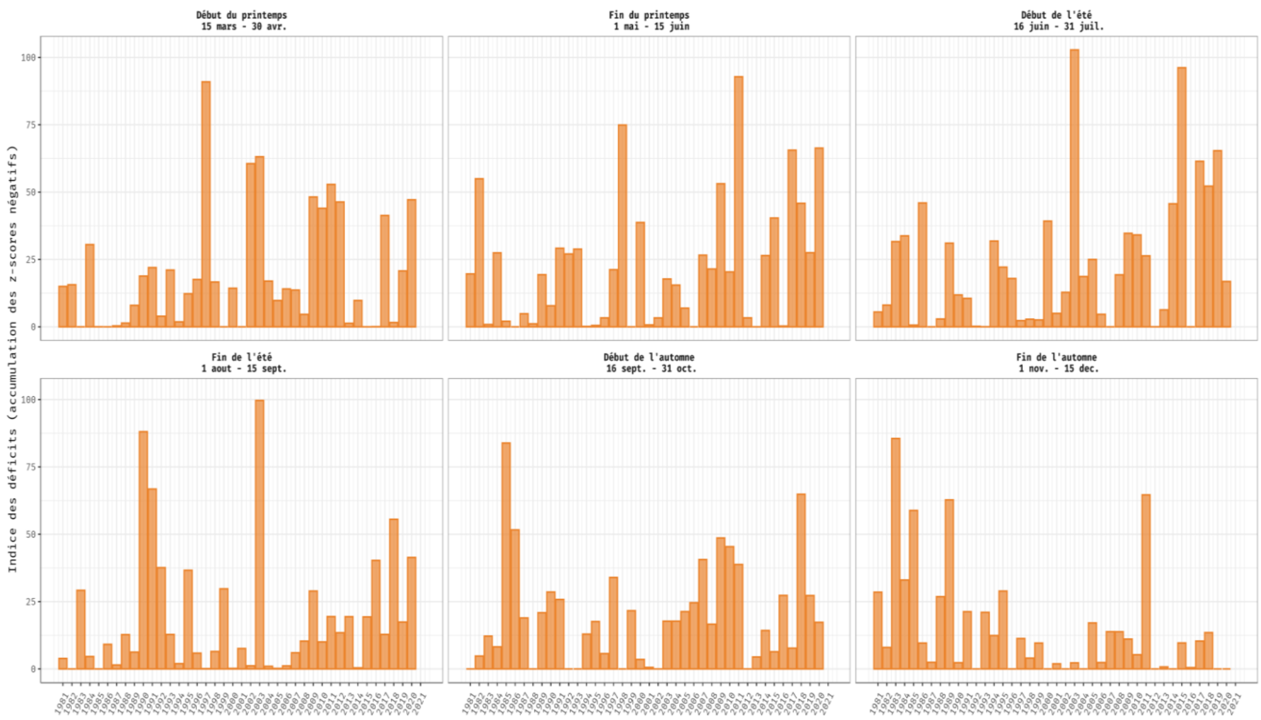

Figure 6: Deficit indexes (=absolute Z-scores accumulated), 6 periods of each year, Orbe, 1981-2020 (Step 7).

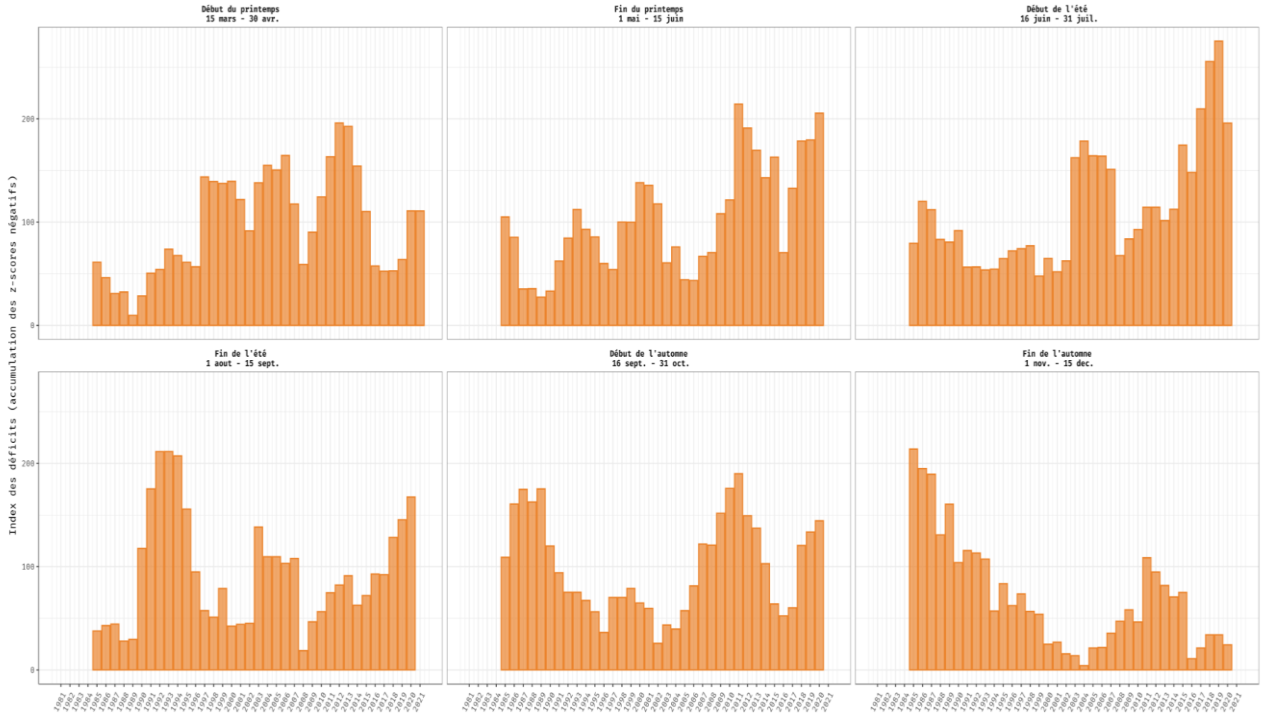

Figure 7: Computation of the deficit indexes (=absolute Z-scores accumulated) in a 5 years time window, Orbe, 1981-2020 (Step 8).

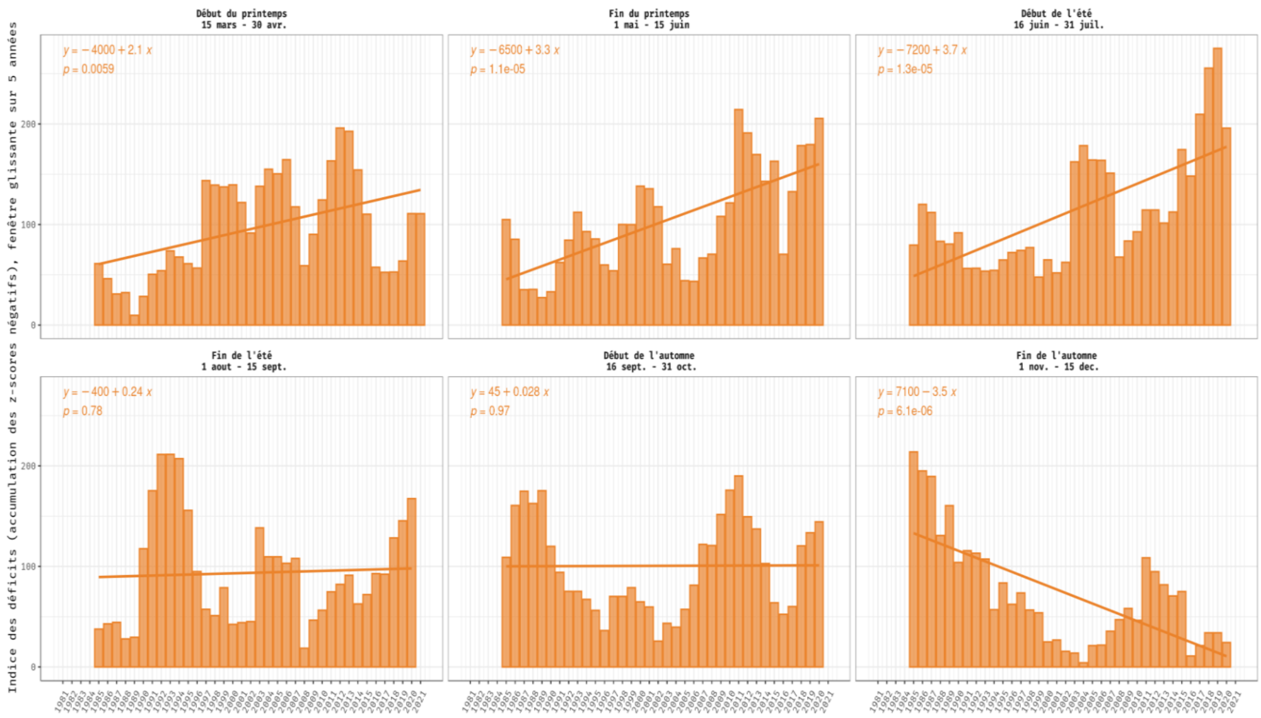

Figure 8: Linear regression model applied on the deficit indexes (=absolute Z-scores accumulated), 5-year average, Orbe, 1981-2020 (Step 9).

4. Results and discussion

4.1. Results of the linear regression model

The p-value of the anomalies trend over 40 years was analysed for each municipality (see chapter 3.2). A trend map illustrates, on one hand, if the trend is not statistically significant (gray color) and, on the other hand, in which direction the trend is going when it is statistically significant (Figure 9 and figure 10).
In others words, the trend is not staticsally significant in the municipalities colored in gray; while the trend is statistically significant (α=0.05) for the colored municipalities. The color code enables to visualise the direction and the intensity of the trend, namely the value of the slope of the regression line equation.
Regarding the deficicit indexes (Figure 9), the red color shows a significant increase of the water deficits, while the green color indicates a significant decrease of the water deficits.
Similarly, in the figure 10, the blue color represents a significant increase of the water excess and the light brown color depicts a significant decrease of the water excess.

The trend map sould be interpreted with cautious as the difference between two municipalities is not evaluated. The analysis is only done within the municipality itself. Indeed, the map might exhibit two municipalities with different colors although their trends are very close because the values obtained are in the vicinity of the 5% significance threshold (slightly above or slightly below 5%).
Moreover, the value of the slope, characterized with the color code, is the best estimate of that value. Actually, we observed that the slope values for different municipalities overlap when considering the 95% confidence interval (range of slope values possible at a 95% confidence) (Annex 2). These results demonstrate that there are little differences between the municipalities in term of anomalies trends.
Although differences between municipalities are extremely small, the differences between periods of the year within a municipality are more pronounced.

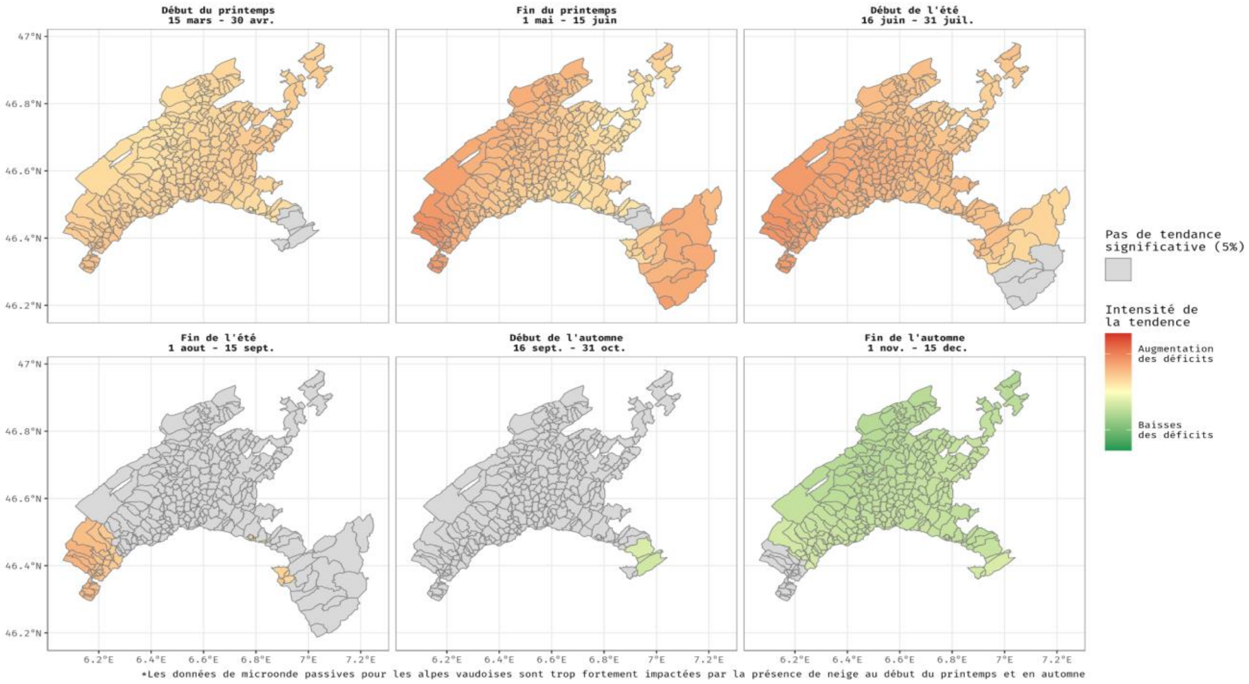

Figure 9: Trend map of the soil moisture deficit indexes, canton of Vaud, 1981-2020.

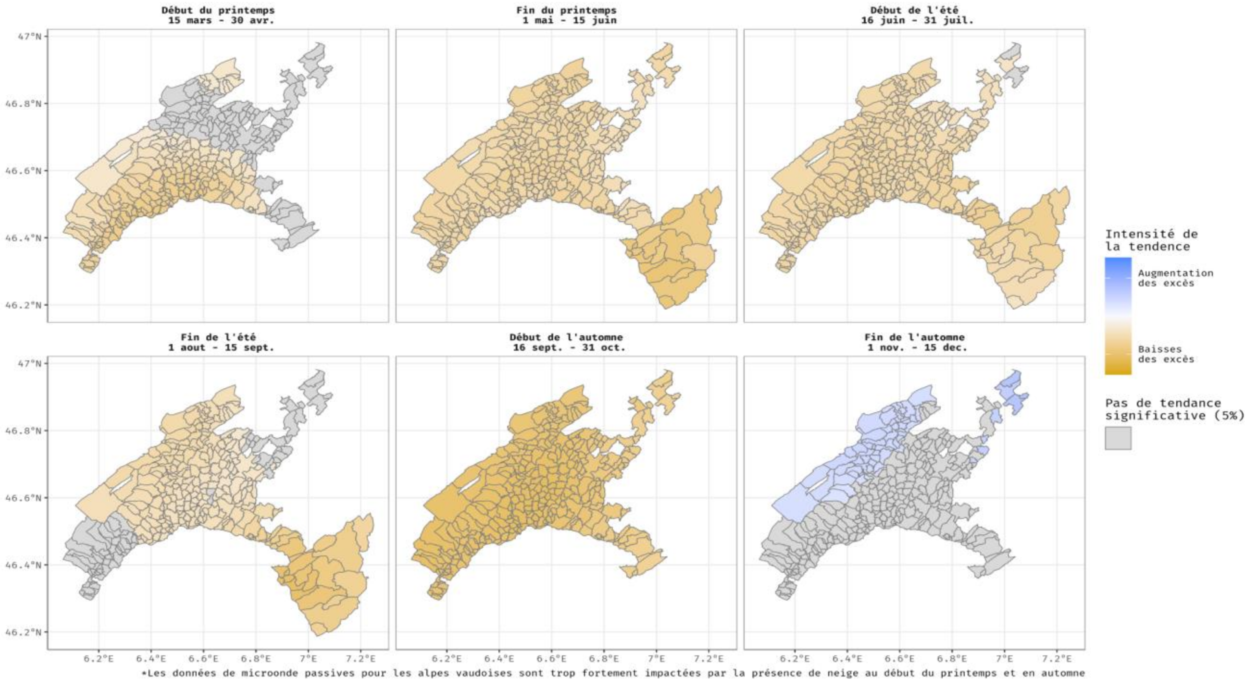

Figure 10: Trend map of the soil moisture excess indexes, canton of Vaud, 1981-2020.

4.2. Soil moisture indicators and yields data correlation

One of the goals of this study was to investigate the correlation of soil moisture indicators (deficit and/or excess) with the yields (t/ha) of selected crops. The different crops of canton of Vaud have been studied based on their vulnerability regarding the soil moisture deficit, the Utilised Agricultural Area (UAA), and their economic weight for the canton of Vaud. The aim of this analysis was to identify crops for which it would be relevant (and correct) to correlate yield data and soil moisture indicators.
Finally, the Federal Statistical Office (FSO) press release and the agricultural report from the Federal Office for Agriculture (FOAG) were read to identify the impact of weather conditions since 2000 on the production of selected crops (Annexes 3 and 4). An example of the FSO press release in French is also given in the annexes (Annex 5).

- **Crops selection**

First, we excluded the crops that are already irrigated i.e orchards and berries, vegetables and strawberries, and potatoes (Table 1). Undoubtely, it would not make sense to conduct a correlation of yield data and soil moisture indicators of crops already irrigated over the last 10 years.

According the 2021 data fom the FSO, the share of the UAA irrigated by crop types for the year 2016 are captured in the table below:

Table 1 : Share of UAA irrigated in %[a] by crop types in 2016 (FSO, 2021).

Crop types	2016 min. (%)	2016 max. (%)
Cereals and maize	2.1	5.5
Orchards and berries	44.3	97
Vegetables and strawberries	63.4	95.7
Potatoes	23.2	48.8
Sugar beets	1.5	7.4
Vine	1.8	6.4
Artificial and permanent grasslands	0.7	2.4

[a]95% confidence interval

Despite a low percentage of irrigated surfaces for the vine, this crop is also excluded in this study. Indeed, it is known and accepted in Switzerland that the vine is a crop which improves in quality during water stress and which benefits, up to a point, from the increase in temperatures in terms of yield. Additionnally, in Switzerland there are others factors that might have influenced the yield of this crop the past years such as cultural practices and new varieties.

These data are to be taken with cautious because they are established on sample survey of agricultural holdings and then extrapolated to the entire canton of Vaud.
Although these statistics are not precise, they are still data available and give an idea of the crops vulnerability concerning water availability.

Then, we shared the UAA in percentage by main crops in 2019 according the inventory of the crops by codes obtained from the General Directorate for Agriculture and Veterinary affairs of canton of Vaud (DGAV, Direction générale de l'agriculture, de la viticulture et des affaires vétérinaires).

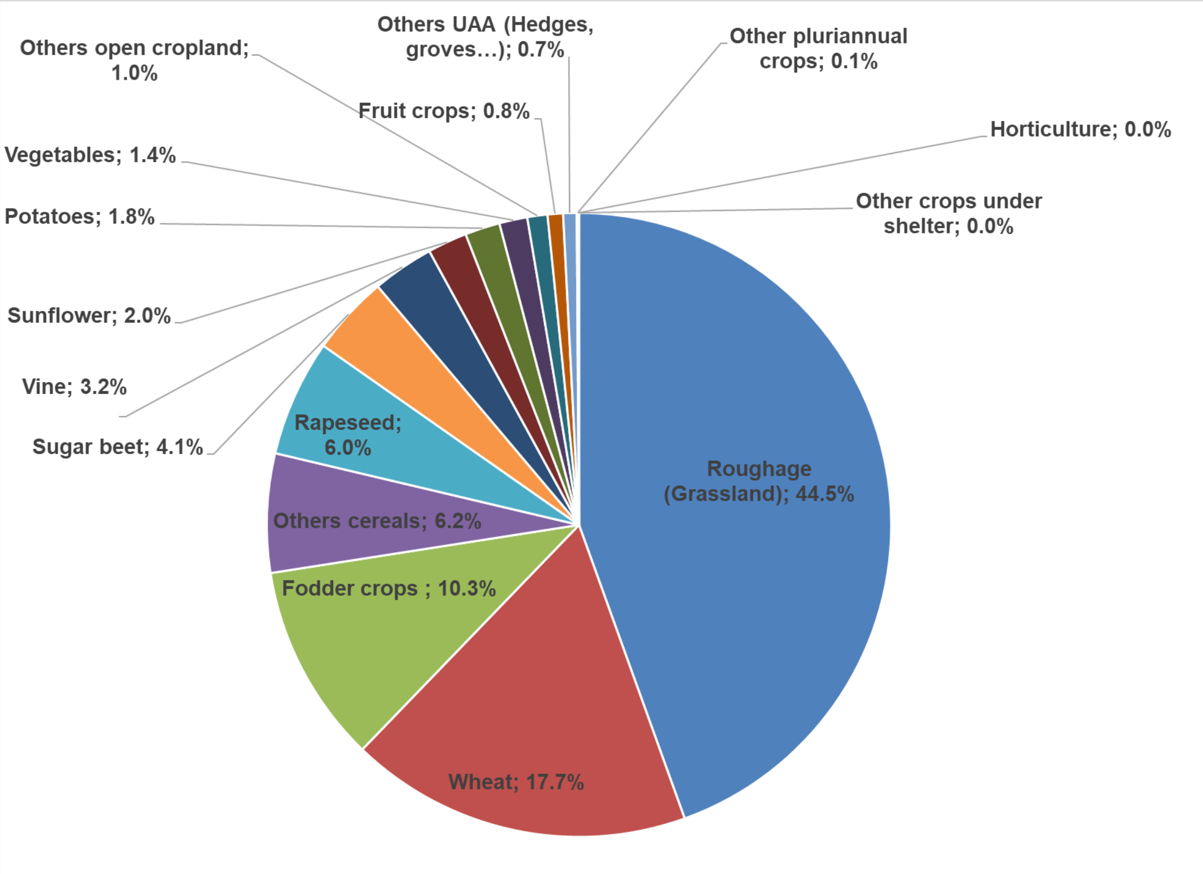

Figure 11: Distribution of UAA in % (DGAV, 2019).

In canton of Vaud, the wheat crop and the grassland (artificial meadow and permanent grassland, i.e "600" codes from the inventory of UAA) counts for almost two-thirds or the total UAA, with respectively 17.7% and 44.5% of the UAA in 2019 (Figure 11).

Since 2003, the FSO is compiling the Economic Accounts for Agriculture (EAA) with the help of Agristat (the statistical department of the Swiss Farmers Union). The EAA describe the economy of the agriculture in Switzerland. Then the data are downscaled at the canton level with the release of the Regional Accounts for Agriculture (REAA).
The "top-down" approach applies to most accounting positions, with a few exceptions such as viticulture, which is assessed at the cantonal level before being aggregated to obtain the Swiss value.

For more details about the methodology, please refer to the document[9] :
Les comptes économiques et satellites du secteur primaire: méthodes - Une introduction à la théorie et à la pratique - 4ème édition | Publication | Office fédéral de la statistique (admin.ch)

The REAA give an idea of the economic values of the different agricultural productions in canton of Vaud (Figure 12). As much as possible, we aggregated the positions retrieved from the REAA to match with the distribution of the UAA illustrated in the figure 11.
For example, the vine crop is only about 3.2% of the UAA in 2019 and represents 209 million CHF (wine grapes and table grapes included).

Through this analysis, we identified mainly two crops to correlate the yields versus soil moisture indicators based on their importance in the UAA share, their economic weight and if they are generally irrigated or not:

- The wheat:

It counts for almost 20% of the cultivated land area in the canton of Vaud in 2019 and it is not ususally irrigated (Table 1). Despite an important part of the UAA, the output value of the wheat is relatively low (Figure 12).
This is explained because the output value of less than 3’000 CHF/ha takes in account the yield X price and is lower than the average output value per hectare of ca. 11’000 CHF/ha. (The prices are respectively 50 CHF/dt for “Suisse Garantie”, 53 CHF/dt for “IP Suisse”, and 107 chf/dt for “Bio” (= organic label) in 2016 as described in the report about the analysis of the Vaud cereals and oilseeds sector.[10])
The canton of Vaud is considered as the breadbasket of Switzerland, and as such it plays an important role in the supply of wheat for the Swiss population. Indeed, the canton of Vaud is the first producer of wheat with 23% of the Swiss output value in 2019 (FSO, 2020).

- The grasslands (artificial meadow and permanent grassland):

In canton of Vaud, the grassland is a large part of the UAA (Figure 11), and the irrigation is not a practice commonly applied to this crop (Table 1).
The output value of the grassland (roughage) might appear low with about 7% of the total value of agriculture in 2019. However, if you add to it the value of the milk, the slaughter cattle and others ruminants, the overall value of the grassland production would be significantly higher (Figure 12).

[9] Murbach F, Amstutz T, Giovanettina S, Giuliani S (2021). Les comptes économiques et satellites du secteur primaire : méthodes. Office Fédéral de la statistique (OFS), 1-120.
[10] Rey D (2018). Analyse de la filière vaudoise des céréales et oléagineux. Direction générale de l’agriculture, de la viticulture et des affaires vétérinaires (DGAV), 1-54.

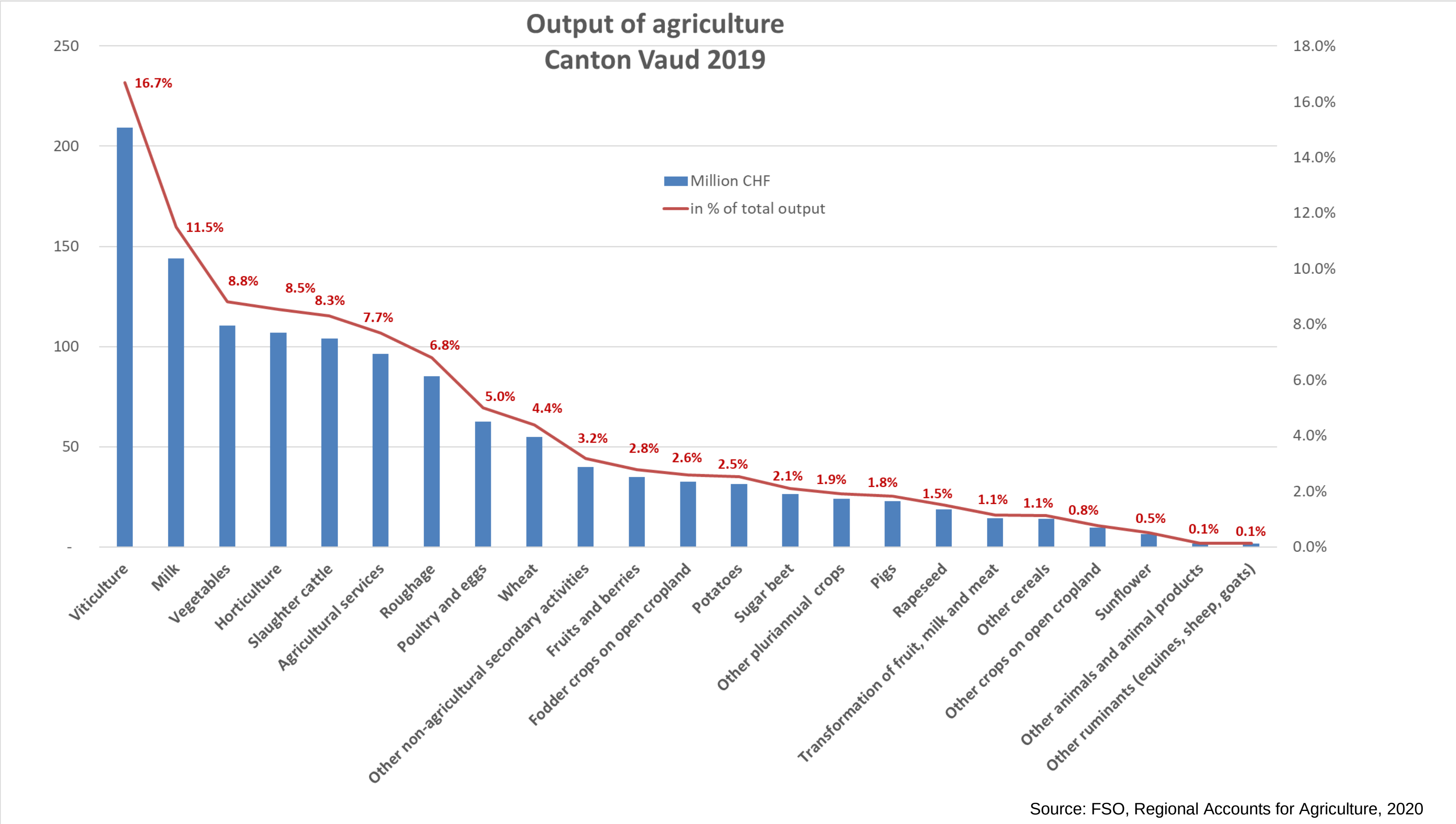

Figure 12: Output distribution of agriculture, canton of Vaud, 2019 (FSO,2020).

- **Yield Data**

According the previous analysis and with the objective to carry out the correlation with soil moisture indicators, we tried to obtain consistent time series of yield data for wheat and grassland production over the last 40 years in the canton of Vaud. In the following chapter, we capture the different researches, interviews and information collected to obtain yield data at the level of the canton.

- The wheat:

The FSO is publishing different statitics based on Agristat data and surveys of agricultural structures. Regarding the wheat, the quantities harvested are obtained by multiplying the area cultivated (surveys of agricultural structures, FSO) by the average yield estimated (USP/Agristat survey). This calculation is done at the level of Switzerland and then broken down at the canton level according the wheat UAA.

Swissgranum is the association that gathers the different actors in the Swiss cereals, protein crops and oilseeds sector. Swissgranum works to defend the interests of the sector.
M. Scheuner, director of Swissgranum, explains that Swissgranum mandates Agristat to conduct two assessments of the quantity of wheat based on surfaces and an average yield (farmers surveys) before the harvest (February, may). During the harvest, Swissgranum performs surveys in about 30 grain collection centers to estimate the harvest quantity. After the harvest, another survey in all grain collection centers is realised and these figures are validated with Agristat. Based on this, a common figure of the national yield is communicated. For data protection reasons, the rule to give only national figures is applied.

The cereal sub-sector that meets the specifications for integrated production ("IP-Suisse" label) represent 35% of the production in canton de Vaud. Thus, M. Demierre, Manager IP-SUISSE Lausanne, has been contacted and was able to provide "IP-Suisse" wheat data for the canton of Vaud since 2003. Before that the data were not collected in a database. Unfortunately, 17 data points is not enough to be able to perform a relevant correlation.

Moreover, the analysis[11] of the Vaud cereals and oilseeds sector depicts the flow of cereal volumes between neighboring cantons and reflects the complexity to obtain precise yield data for the canton.

[11] Rey D (2018). Analyse de la filière vaudoise des céréales et oléagineux. Direction générale de l'agriculture, de la viticulture et des affaires vétérinaires (DGAV), 1-54.

<u>- The grasslands (artificial meadow and permanent grassland):</u>

M. Giuliani from Agristat assesses the production on the basis of indirect information, such as animal herd, surfaces, weather, slaughterings, etc. Some importation data are also available and would be an indirect indicator of the grassland production but precise readings are needed to assess the impact of soil moisture on production.

Agroscope has grass growth data collected from several sites over several years. Therefore, more investigation could be performed to compare the annual yields obtained to the anomalies calculated with the VanderSat technology, taking into account its resolution.

In short and to conclude, it was not possible to obtain precise, consistent, and long (40 years) time series of yield data for the wheat and the grassland for the canton of Vaud as imagined at the beginning of the study.

- **FSO press release and FOAG agricultural report**

As the yearly yield and quality of a crop production are dependent on meteorological parameters occurring during the different seasons (water excess, water deficit, temperatures, frost, hail…), it was interesting to read the press releases available to have a qualitative overview of the weather effect on the yield from 2000 to 2020.

The extraction of wheat-related parts of press releases (Annex 3) shows that the yield of wheat is relatively affected by wet conditions in autumn, and spring; while water excess in summer will impact its quality. Although an extended period with a lack of water during the growing season will of course influence the yield, the wheat seems more sensitive to water excess than to water deficit.
As for the grassland, the reading of the press releases (Annex 4) for the same period indicates that the yield decrease for the years with dry and hot summer.

4.3. Data visualisation: "Anomalies historical maps"

The goal of this short study was also to create a visual support to communicate the need to anticipate climate change, and in particular, with regard to the resource "water" (Chapter 1.3). As previously, explained the trend maps (Chapter 4.1) can be misunderstood and for this reason, they should not be used for any communication purpose.

In contrast, maps depicting the evolution of anomalies (Z-scores accumulated) by decade are ideal to communicate. We will call them "Anomalies historical maps" (Figure 13).
The columns are equivalent to the years and the rows represent the different periods of the year, from early spring to the end of autumn (Figure 13). As for the colors, the red color describes drier conditions or accumulated negative anomalies, while blue color indicates wetter conditions or positive accumulated anomalies (always in comparison with the reference period 1981- 2010).

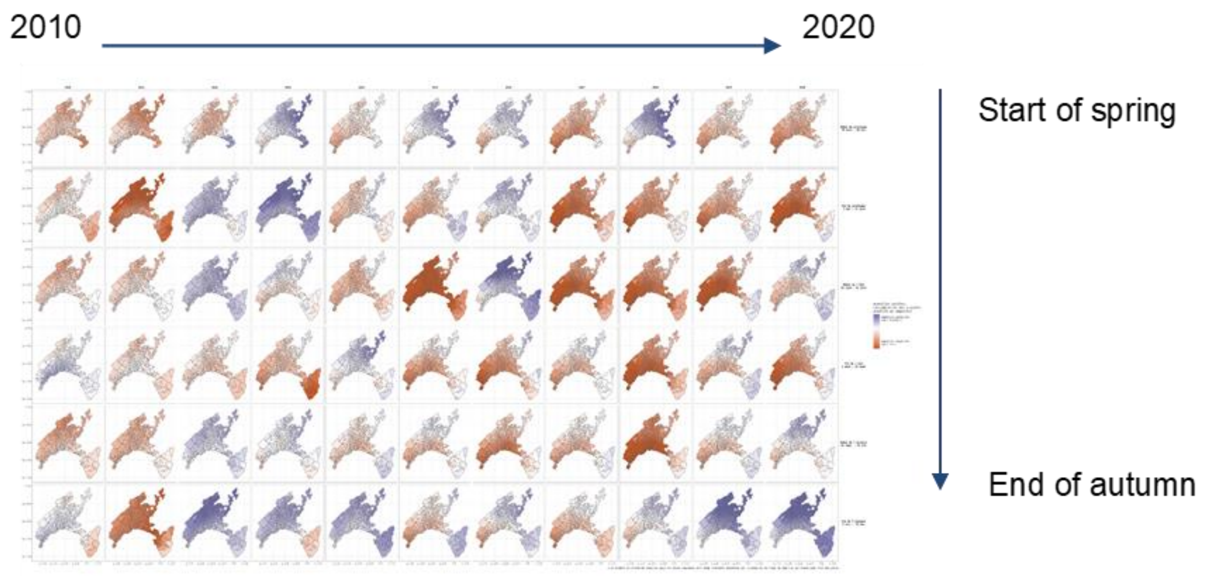

Figure 13: Method to read an "Anomalies historical map".

Such maps describe at a glance the trend of anomalies over time and really speak for themselves. Typically, in the decade 2000 to 2010, everybody will remember the very dry and hot summer of 2003 (Figure 16). More recently, the figure 17 shows that 2018 had a very extended period of hot and dry conditions resulting in a low soil moisture content.

The anomalies historical map of the last decade (Figure 17) demonstrates more years with intense soil moisture deficits compared to the climate normal.

Figure 14: Anomalies historical map[a], decade 1981 – 1990.

[a] For the Vaud Alps, the passive microwave data are too strongly impacted by the presence of snow in early spring and were not analysed.

Figure 15: Anomalies historical map[a], decade 1990 – 2000.

[a] For the Vaud Alps, the passive microwave data are too strongly impacted by the presence of snow in early spring and were not analysed.

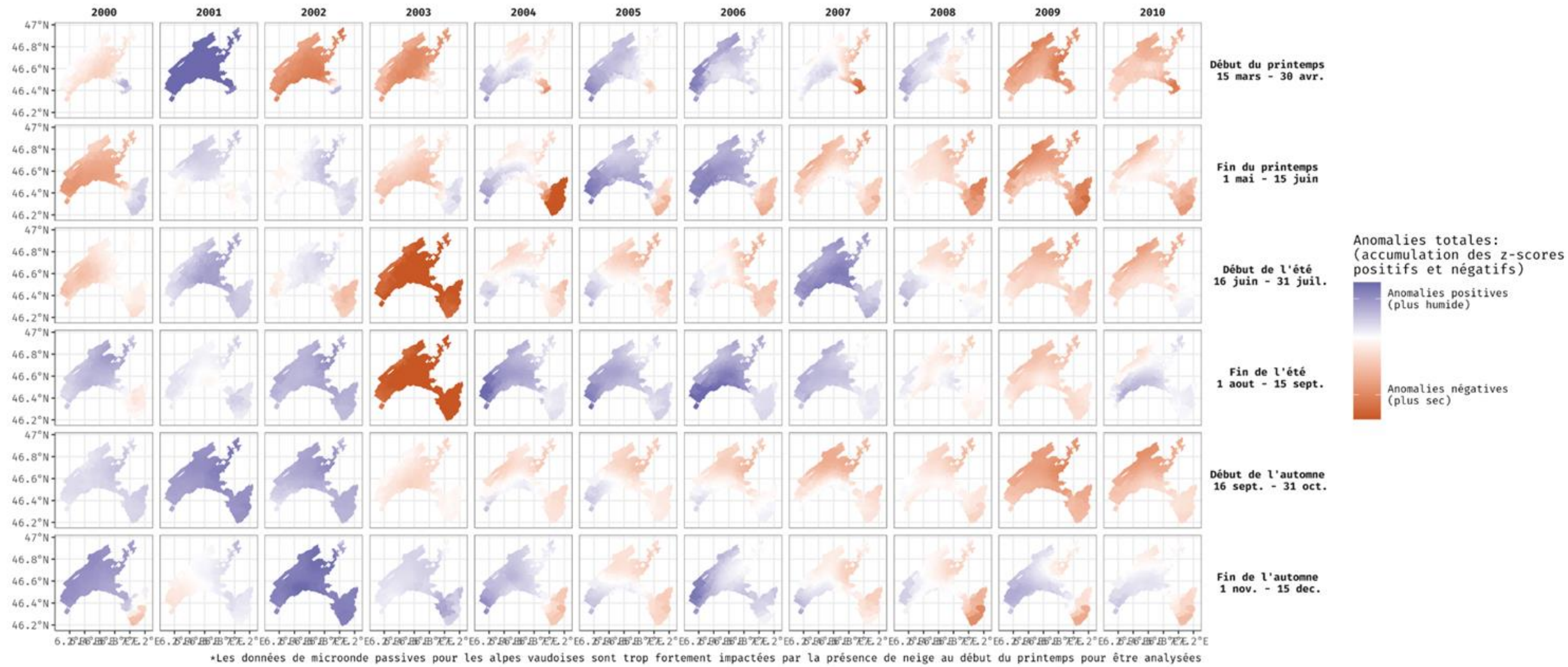

Figure 16: Anomalies historical map[a], decade 2000 – 2010.

[a] For the Vaud Alps, the passive microwave data are too strongly impacted by the presence of snow in early spring and were not analysed.

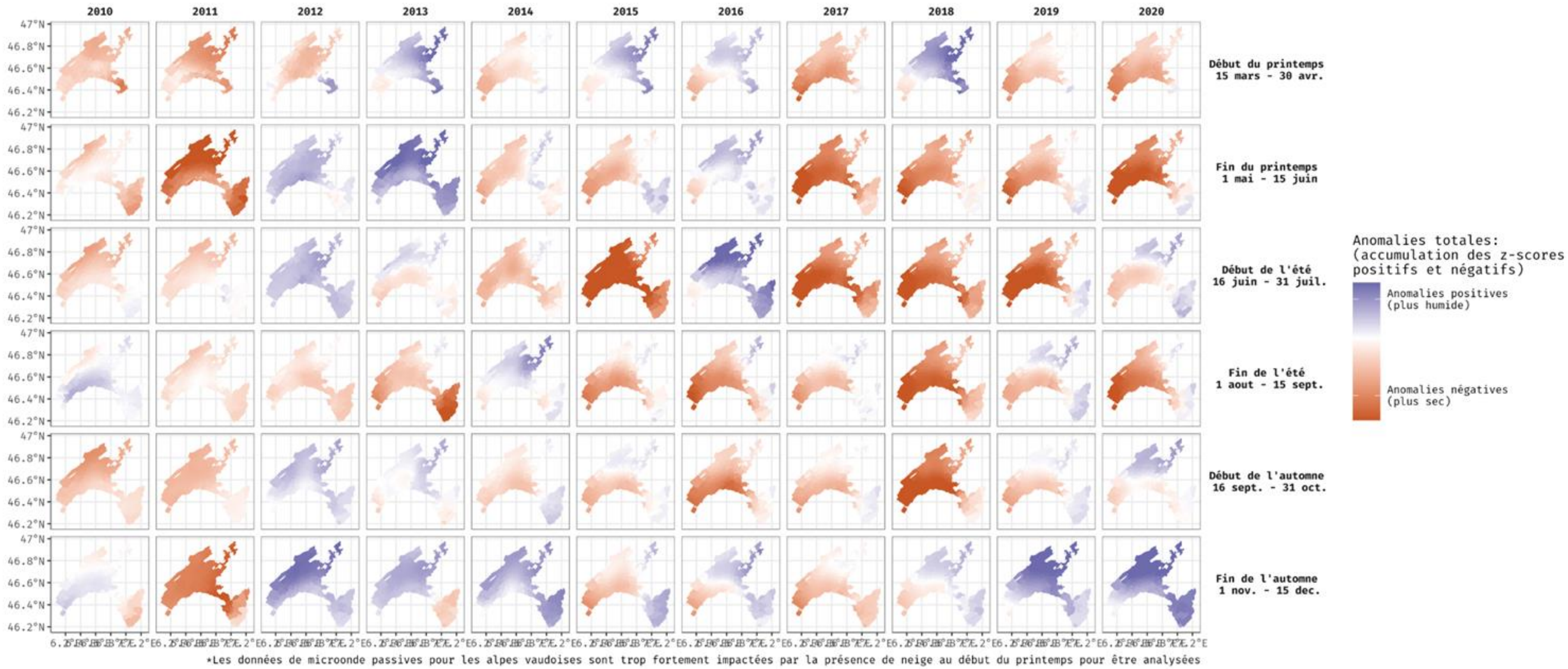

Figure 17: Anomalies historical map[a], decade 2010 – 2020.

[a] For the Vaud Alps, the passive microwave data are too strongly impacted by the presence of snow in early spring and were not analysed.

4.4. Discussion

Overall, the soil moisture deficit increases during the last 40 years, especially at the end of spring and beginning of summer. Lack of water at these times of the year has consequences on the growth of both winter and summer crops. Contrary, in late autumn an increased excess water is reported and might affect winter crops.

An overlap of the 95% confidence interval of the slope values (obtained from the regression model) is noted, and exhibits that trend is similar for all municipalities. The canton of Vaud is following the same trend and there are only little differentiation at the regional level.
The difference in climate trends differ very slightly between municipalities and cannot be the main reason to choose measures. It means that the climate adaptation measures should be defined depending on the possibility to change the production systems regionally. For example, some municipalities might have some production systems that are less vulnerable to soil moisture deficit, while others might have the capability to irrigate at a low cost.

The temperature rise over the last 150 years is well documentated[12]. In view of this temperature increase, the crops will develop earlier and might suffer from a higher soil moisture observed at the beginning of the spring (According the climate normals 1981-2010, the beginning of the spring is wetter than the end).The result might be as important as the effect of the soil moisture trend itself.

4.5. Limitation and additional analyses

Passive microwave data are affected by the presence of snow and ice. When water is in its solid form (ice or dry snow), it is not mobile anymore and its interaction with the passive microvawe is reduced (it does not absorb passive microwaves anymore). This is why the analysis wasn’t done during the winter months and for early spring in the case of the Vaud Alps.

As for the statistical method, the use of a parametric statistical model (ordinary least square linear regression) implies that assumptions are fulfilled (e.g independence of the observation, heteroscedasticity, etc.).
However, 40 years of data is relatively short to verify those assumptions as the climate is defined worldwide to be the average of the last 30 years (climate normals). Thus, those assumptions were not verifed. A non-parametric model, such as the Mann-Kendall test, would be statistically more robust, but also more challenging to explain and interpret.
In order to study the climate, additional analyses of longer time series (for example a precipitation and temperature datasets[13]) could be relevant to identify clearer trends.
Nevertheless, this type of analysis might highlight a trend that is already too old since agriculture is adapting very quickly. Furthermore, precipitation and temperature data are not direct indicators of water available to plants (compared to soil moisture). Finally, this study focuses on the trend observed in the past 40 years. Some forward-looking models exist for Switzerland (precipitation and temperature) and they might give a more accurate picture of the future climate than assumptions based on past trends.

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[12] NCCS (National Centre for Climate Services), 2021. Observed climate change in Switzerland. NCCS, accessed on 23.12.2021, https://www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/swiss-climate-change-scenarios/observed-climate-change-in-switzerland.html.
[13] NCCS (National Centre for Climate Services), 2021. CH2018 Web Atlas. NCCS, accessed on 23.12.2021, https://www.nccs.admin.ch/nccs/en/home/data-and-media-library/data/ch2018-web-atlas.html.

5. Conclusion

The overall objective of this work was to assess the soil water content over the last 40 years at the canton and the municipality levels in order to retrieve potential trends and their impacts on agricultural production. Indeed, the soil moisture measurement has the benefit to be a good indicator of the water availability for plants by considering indirectly temperature, precipitation, soil texture, runoff… The interest of this short study was to tailor it to the agricultural needs in canton of Vaud by spliting the year in 6 periods to study both water deficits and water excesses during the growing period.

In summary, over the last 40 years, this study shows an increase of the soil water deficit at the end of spring and beginning of summer, as well as an increase of the soil water excess at the end of autumn. Consequently, both winter and summer crops might suffer from a lack of water in late spring and early summer, while the winter crops would be affected by wetter conditions at the end of autumn. Futhermore, the crops might develop earlier due to increased temperature and be exposed to higher soil moisture at the very beginning of spring.
Unfortunately, it was not possible to obtain consistent and reliable yield data for 40 years at the level of canton of Vaud. Therefore, a correlation analysis between crop yields and soil moisture was not conducted.

Another key finding of this study is that the trends are similar for the whole canton of Vaud. Accordingly, the decision makers of the canton should focus their efforts on developping relevant measures based on the aptitudes of each region to modify their productions systems. An analysis of the production systems and their adaptation capabilities might help to prioritize meaningful strategies locally. On that purpose, it is of paramount to have a global vision and to reflect in terms of irrigation facilities, regional drains[14], new cultivars, water retention, alternative crops and agricultural practises. Indeed, although the increase in temperature and the lack of water may seem to be priorities, on a shorter-term vision, some crops such as the wheat appear to be more impacted by water excess[15].
Assuming that the trends observed continue to evolve in the same direction, these results agree with a release done afterwards by the NCCS[16] (National Centre for Climate Services) which concludes that in the future the temperature will increase, the summer will be drier and there will be more rains in winter in the canton of Vaud. In that context, Agroscope[17] has also published a recent paper that estimates an increase of about 20% in irrigation needs by the time horizon 2045-2074, regardless of the crop types and sites. The major changes are predicted to be in summer and in autumn.

This short study suggests the potential of using data from remote sensing observations to monitor key agricultural parameters such as soil moisture. This technology can serve as an useful tool for water management and irrigation in a close future.
Further investigations, in the hands of Research, could deepen this topic and foster innovation in agriculture.

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[14] Deillon S (2021). Drainages en Zone Agricole : Maintenir et rénover le réseau existant. Agri, 40, 3.
[15] Schmid D (2020). Grandes cultures : Les années chaudes sont plus favorables que les années pluvieuses. Agroscope Transfer, 328, 1-5.
[16] NCCS (National Centre for Climate Services), 2021. Climate change in the Swiss cantons. NCCS, accessed on 23.12.2021, https://www.nccs.admin.ch/nccs/en/home/regions/kantone.html.
[17] Eisenring S, Holzkaemper A, Calanca P (2021). Berechnung der Bewässerungsbedürfnisse unter aktuellen und zukünftigen Bedingungen in der Schweiz. Agroscope Science, 107, 1-55.

Conclusion

A travers cette étude, l'objectif global était d'évaluer l'humidité dans le sol des 40 dernières années à l'échelle de la commune et du canton de Vaud afin d'extraire des tendances éventuelles et leurs impacts sur la production agricole. En effet, la mesure d'humidité dans le sol a l'avantage d'être un bon indicateur de la disponibilité de l'eau pour les plantes en prenant en compte indirectement la température, les précipitations, la texture du sol, le ruissèlement… L'intérêt de cette courte étude était de l'adapter aux besoins de l'agriculture Vaudoise en divisant l'année en 6 périodes pour étudier à la fois les déficits et les excès hydriques pendant la période de croissance.

En résumé, au cours des 40 dernières années, cette étude montre une augmentation du déficit hydrique du sol à la fin du printemps et au début de l'été, ainsi qu'une augmentation de l'excès d'eau à la fin de l'automne. Par conséquent, les cultures d'hiver et d'été pourraient souffrir d'un manque d'eau à la fin du printemps et au début de l'été, tandis que les cultures d'hiver seraient touchées par des conditions plus humides à la fin de l'automne. De plus, les cultures pourraient se développer plus tôt en raison de l'augmentation connue des températures et être exposées à une humidité du sol plus élevée au tout début du printemps.
Malheureusement, il n'a pas été possible d'obtenir des données de rendement cohérentes et fiables au niveau du canton de Vaud, pour les 40 dernières années. Ainsi, une analyse de corrélation entre les rendements des cultures et l'humidité du sol n'a pas été effectuée.

Une autre conclusion clé de cette étude est que les tendances sont similaires pour l'ensemble du canton de Vaud. En conséquence, les décideurs du canton devraient concentrer leurs efforts sur l'élaboration de mesures pertinentes basées sur les aptitudes de chaque région à modifier leurs systèmes de production. Une analyse des systèmes de production et de leurs capacités d'adaptation pourrait aider à prioriser des stratégies judicieuses localement. A cet effet, il est primordial d'avoir une vision globale et de réfléchir en termes d'infrastructures d'irrigation et de drainage[18], de nouveaux cultivars, de stockage de l'eau, de cultures alternatives et de pratiques agricoles. En effet, bien que l'augmentation de la température et le manque d'eau puissent sembler être des priorités, certaines cultures comme le blé apparaissent plus impactées par l'excès d'eau[19].
En supposant que les tendances observées continuent d'évoluer dans le même sens, ces résultats concordent avec un communiqué publié ensuite par le NCCS[20] (National Centre for Climate Change) qui conclut qu'à l'avenir la température va augmenter, l'été sera plus sec et il y aura plus de pluies en hiver dans le canton de Vaud. Dans ce contexte, Agroscope[21] a également publié une étude récemment qui estime une augmentation d'environ 20 % des besoins en irrigation à l'horizon 2045-2074, quels que soient les types de cultures et les sites. Les principaux changements devraient se produire en été et en automne.

Cette courte étude suggère le potentiel d'utilisation de données de télédétection pour surveiller les paramètres agricoles clés tel que l'humidité du sol. Cette technologie se présente comme un outil utile pour la gestion de l'eau et l'irrigation dans un futur proche. D'autres investigations, entre les mains de la Recherche, pourraient approfondir ce sujet et favoriser l'innovation dans l'agriculture.

[18] Deillon S (2021). Drainages en Zone Agricole : Maintenir et rénover le réseau existant. Agri, 40, 3.
[19] Schmid D (2020). Grandes cultures : Les années chaudes sont plus favorables que les années pluvieuses. Agroscope Transfer, 328, 1-5.
[20] NCCS (National Centre for Climate Services), 2021. Climate change in the Swiss cantons. NCCS, accessed on 23.12.2021, https://www.nccs.admin.ch/nccs/en/home/regions/kantone.html.
[21] Eisenring S, Holzkaemper A, Calanca P (2021). Berechnung der Bewässerungsbedürfnisse unter aktuellen und zukünftigen Bedingungen in der Schweiz. Agroscope Science, 107, 1-55.

6. Annexes

ANNEXES	DESCRIPTION	
1	Soil moisture excesses analysis, case of municipality of Orbe.	/
2	Example of confidence interval of the regression slope value.	/
3	Cereals quantity and quality, period 2000-2020.	File enclosed
4	Roughage/Grassland quantity and quality, period 2000-2020.	File enclosed
5	Example of the FSO press release	File Enclosed

6.1. Soil moisture excesses analysis, case of municipality of Orbe

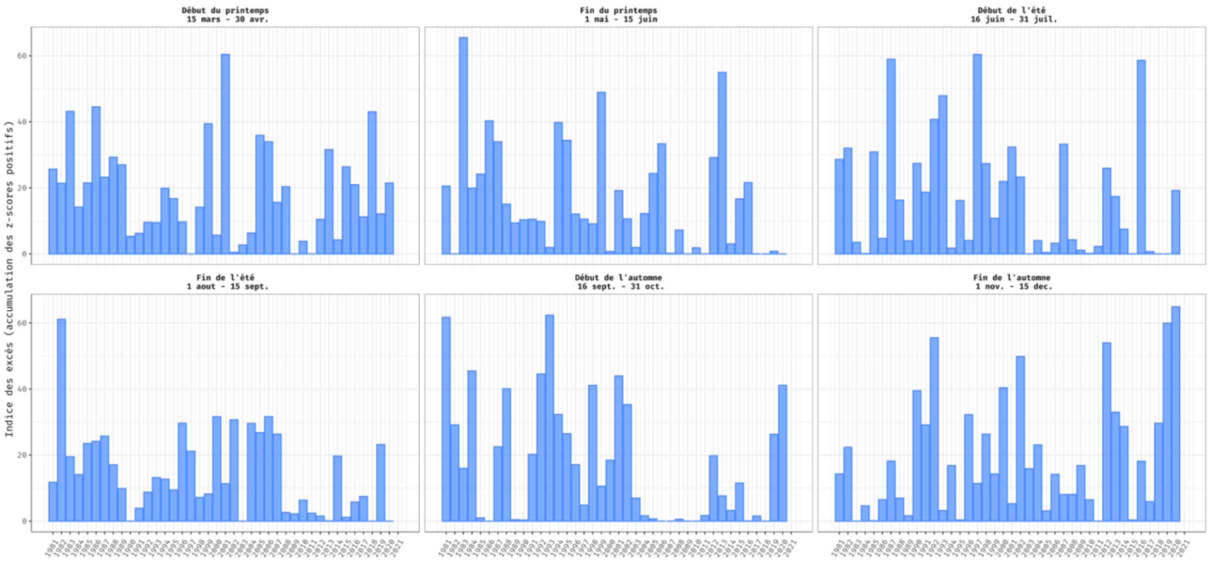

Figure 18: Excess indexes (= Z-scores accumulated), 6 periods of each year, Orbe, 1981-2020 (Step 7).

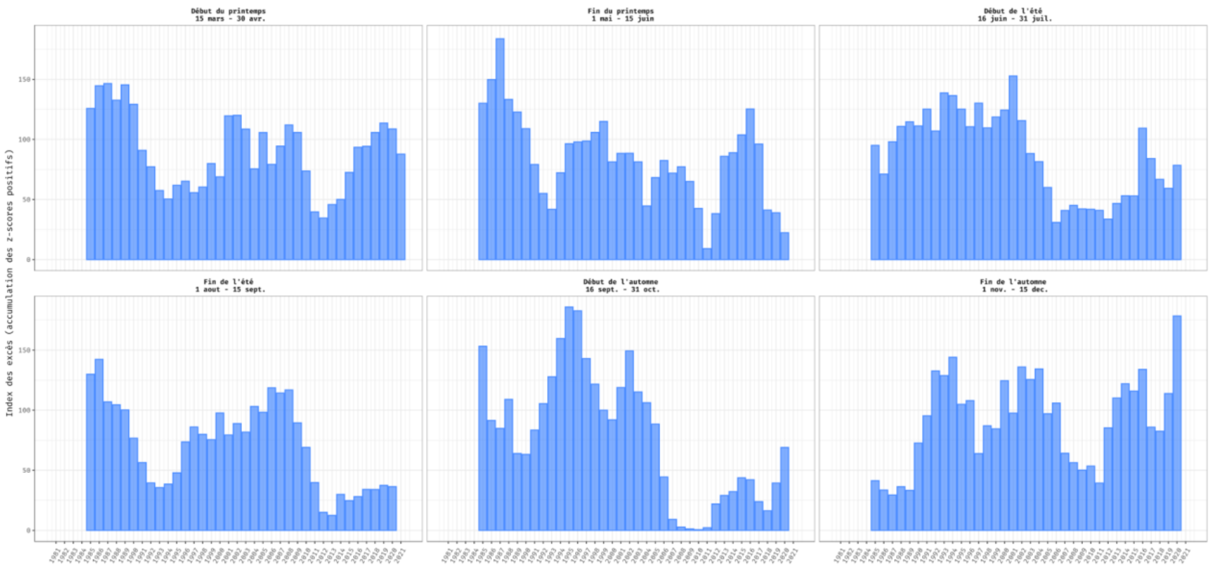

Figure 19: Computation of the excess indexes (= Z-scores accumulated) in a 5 years time window, Orbe, 1981-2020 (Step 8).

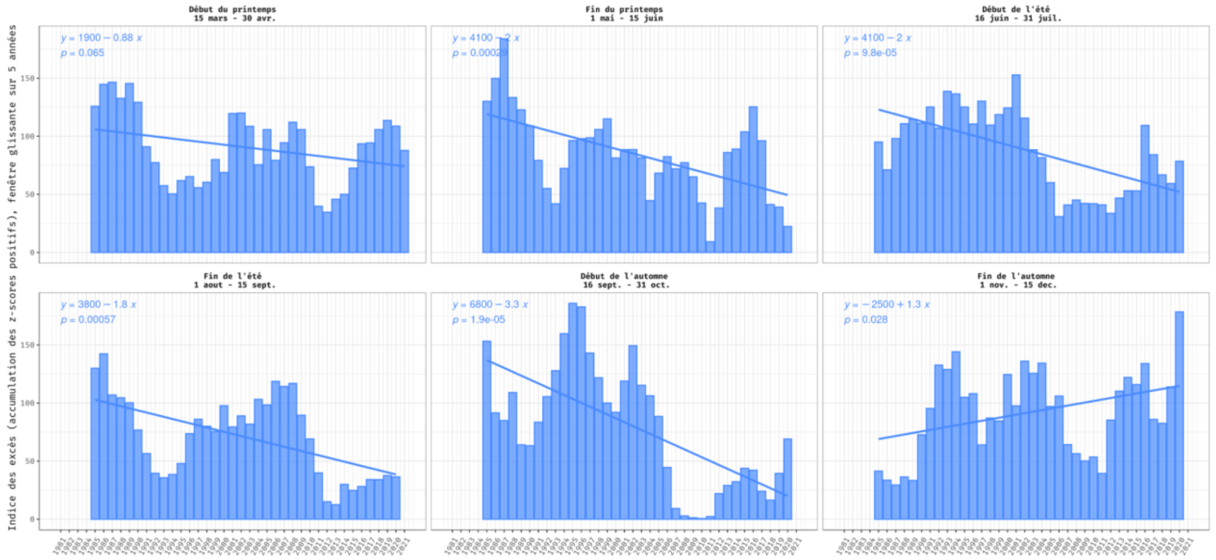

Figure 20: Linear regression model applied on the excess indexes (= Z-scores accumulated), 5-year average, Orbe, 1981-2020 (Step 9).

6.2. Example of confidence interval of the regression slope values

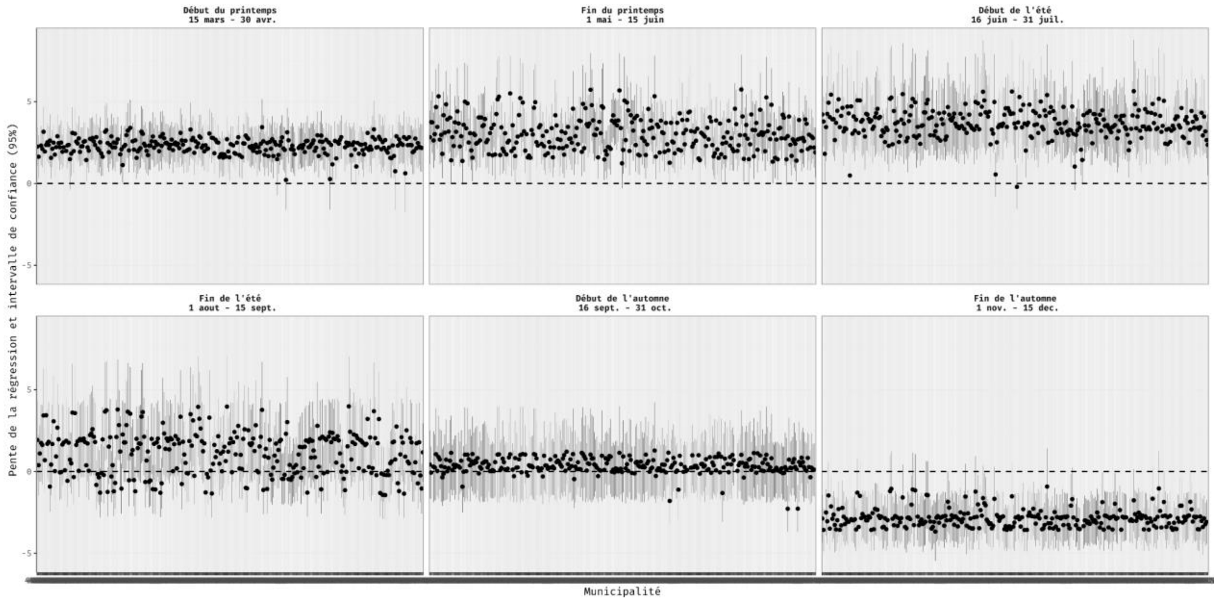

Figure 21: Confidence interval of the regression slope values[a], case of the soil moisture deficits.

[a]Each point represents a municipality and the line represents the range of the confidence interval. The difference between municipalities is relatively small, but the difference between the period of the year might be larger (e.g. if we compare the trend at the start of the summer versus the trend at the end of autumn).

6.3. Cereals quantity and quality, period 2000-2020 (file enclosed)

6.4. Roughage/Grassland quantity and quality, period 2000-2020 (file enclosed)

6.5. Example of the FSO press release (file enclosed)

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