CMT project Report

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1 Deviations from project proposal

The initial idea included finding functional models of multiple physical, biological, and chemical processes that were deeply intertwined and require more time to understand theoretically than to actually code. This idea was too complex to implement thoughtfully in the given time. Moreover, the hypothetical equations we found needed a lot of data that were not easily accessible. For these reasons, we decided to reduce the aim of this project to the analysis of the evolution of the water content and the level of compaction of the root-zone of a soil under intensive agricultural use.

2 Introduction to the problem

2.1 Problematic

In the context of traditional agriculture, the following questions can be asked:

- What is the natural effect of precipitation and plant uptake on the water content of a soil?
- How do natural weather conditions coupled with mechanical work influence soil compaction? A hydrological property on which multiple soil health factors such as permeability and nutrient exchange capacity, depend.

Our interest in this project is to estimate those two parameters for a specific station based on basic meteorological data of the station along with the texture of the soil and the mechanical work. In order to do so, we used a study on the "Effect of cropping systems and climate on soil physical characteristics" [7]. The scope is to implement a model of water content and porosity, and then compare the computed values to the observation of the study.

2.2 A brief description of the parameters and dependencies of our system

Soil water content, as described more deeply in 3, is the percentage of water that the soil contains at a given time. It is a value between 0 and 1 that depends on the different inflows and outflows of water in the soil. Compaction is a significant factor of soil quality as it impacts the porosity (partial volume of fluid phase), and by doing so influences the quality of the habitat the void represents for living organisms, along with the accessibility of water and nutrient to the soil fauna and the plants. Overall, compaction tends to reduce the local environmental health. Moreover a compacted soil will be less resilient to flood event as it has a smaller permeability. Therefore, the compaction of a soil actively reduces the range of ecosystem services a plot of land has to offer. We decided to evaluate the evolution of soil porosity over time as an indicator of the soil compaction under agricultural work, which depends on the present humidity (reason for which we modeled water content), the pressure applied and biological factors such as the quantity of earthworms that we did not consider here.

3 Approach used (e.g., models, mathematical relationships)

3.1 Soil water content modeling (SWC)

The temporal evolution of SWC was simulated with a simplified masse balance model [8] :

$$\frac{\partial S}{\partial t} = (P + I + U) - (R + D + E + Tr)[L/t] \tag{1}$$

where S is the the different parameters are listed in 2. To focus on the arbitrary dominant processes, I, $ET = E + Tr$, and D, the equation becomes:

$$\frac{\partial S}{\partial t} = i - \frac{\partial ET}{\partial t} - D \tag{2}$$

Link between water balance and volumetric water content The model is applied to a soil layer of depth z and unit surface area ($A = 1$ m^2). The soil volume is therefore $V = Az$. The corresponding volumetric soil water content θ cm^3 cm^{-3}, is implemented in modeleWaterContent.c, is

$$\theta = \frac{\Delta S}{V} = \frac{B}{10\,z}, \tag{3}$$

where $B = I - ET - D \qquad$ [mm]

The following equations were used to compute B.

3.1.1 Infiltration

Infiltration is estimated using Philip's analytical solution of Richards' equation for cumulative infiltration [8]: $I(t) = S * \sqrt{t} + A1 * t[L]$ Daily infiltration is computed as the increment $i_d = I(d) - I(d-1)$. where S is the sorptivity and A_1 a gravity-related infiltration coefficient, they are taken from empirical values reported for soils with a texture similar to that of the study site, listed in 2.

3.1.2 Evapotranspiration

Evapotranspiration (ET) is a complex concept and requires comprehension of biological processes as much as physical soil properties. It can however be approximate by Turc's formula (1961) [8], which provides an estimate of potential ET_p at the monthly scale from monthly mean temperature $\overline{T}[C]$ and solar Radiation R_s $[cal/cm^2 day]$:

$$ET_p = 0.4(R_s + 50)\,\frac{\overline{T}}{\overline{T} + 15}[cm/month], \tag{4}$$

Monthly values were converted to daily effects $[mm/d]$ by dividing ET_p by the number of day in the month. The observed value from [9] presents Radiation (GLOT) in $[J/cm^2]$. They are converted as follows: 1 cal = 4.184 J.

3.1.3 Drainage

Drainage, defined as the flux at the bottom of the soil rootzone depends on texutre, underlying rock, and saturation status. It should also be influenced by compaction, but we this effect is hereafter considered negligible. The drainage simulation is parted in 2 cases:

1. The soil is not saturated. To simplify the behavior, the flux has not yet reached the bottom of the rootzone and the matric tension is too high to let water go. $D = 0$

2. The soil is saturated, $D = constant(= 0.001[mm/day])$

3.2 Soil compaction and porosity modeling

Soil compaction was assessed through porosity, derived from bulk density. Porosity n_s is computed following [7] as:

$$n_s(w, P, N, z) = 1 - \frac{\rho_a(w, P, N, z)}{\rho_t(w)}, \tag{5}$$

where ρ_a is the apparent bulk density, ρ_t is the textural density, w is soil water content, P is applied pressure, N is the number of machinery passes, and z is depth This formulation assumes that porosity changes are mainly driven by variations in bulk density, while mineral density remains effectively constant over the range of compaction considered [2]. Textural density varies linearly with water content[3]:

$$\rho_t(w) = \rho_{t,0} + a_t(w - w_0), \tag{6}$$

and bulk density is decomposed into a baseline and traffic-induced increment:

$$\rho_a(w, P, N, z) = \rho_{a,0}(z) + \Delta\rho_a(w, P, N, z). \tag{7}$$

Traffic-induced compaction is modeled as:

$$\Delta\rho_a = k_1 f_w(w) f_P(P) f_N(N) f_z(z), \tag{8}$$

where f_w, f_P, f_N, and f_z capture the effects of soil moisture, applied pressure, number of passes, and depth attenuation, respectively. Depth attenuation follows

$$f_z(z) = \exp(-\lambda z), \tag{9}$$

pressure effect

$$f_P(P) = \left(\frac{P}{P_{\text{ref}}}\right)^{\alpha}, \tag{10}$$

and repeated passes

$$f_N(N) = 1 - \exp(-cN). \tag{11}$$

The water content $w(t)$ from the SWC model directly feeds the compaction model through $\rho_t(w)$ and $f_w(w)$.

3.2.1 Numerical implementation

The automation is done by a Matlab shell, which orchestrates the chain action of the different programs. For this to be feasible, we define a main function for each file which is then called in the driver.m. To prevent any crash due to missing files, each call first verifies the existence of the file. It returns a confirmation message and only then runs the function. The observation of meteorological and agricultural traffic data are preprocessed in Matlab to extract observations and merge them into a continuous time series formatted for model input. The inputs are then passed to the water content and porosity models implemented in C. MATLAB-generated CSV tables were imported using predefined structures. SWC and compaction equations were solved iteratively on a daily time step, updating parameters based on the previous time step. Simulation outputs were saved as CSV files. Finally, MATLAB scripts are used for post-processing and visualization. Simulated soil water content is compared with field observations and modeled porosity is evaluated against available measurements at different depths. All outputs, including intermediate datasets and figures, are stored in a dedicated results directory. command to run driver.m matlab -batch "run('src/driver.m')"

3.2.2 summary of all the parameters used in the code (for the moment only water content)

All parameter values were selected from literature ranges appropriate for silt loam soils, as summarized in Tables 1–2. The model aims to reproduce qualitative trends of hydrological and mechanical soil processes.

Table 1: Terms of the root-zone water balance (bucket model)

Symbol	Description	Units
P	Precipitation	$\mathrm{mm\,d^{-1}}$
I	Infiltration / irrigation input	$\mathrm{mm\,d^{-1}}$
U	Capillary rise from deeper layers	$\mathrm{mm\,d^{-1}}$
R	Surface runoff	$\mathrm{mm\,d^{-1}}$
D	Drainage at the bottom of the root zone	$\mathrm{mm\,d^{-1}}$
E	Soil evaporation	$\mathrm{mm\,d^{-1}}$
Tr	Plant transpiration	$\mathrm{mm\,d^{-1}}$
S	Root-zone soil water storage $\left(\int_0^z \theta\, dz\right)$	mm

Table 2: Soil and model parameters used in the water balance model (silt loam)

Parameter	Symbol	Value	Units	Reference
Sorptivity	S	20.0	$\mathrm{mm\,day^{-1/2}}$	[10, 5]
Gravity infiltration term	A_1	5.0	$\mathrm{mm\,day^{-1}}$	[10, 6]
Saturated water content	θ_s	0.46	$\mathrm{cm^3\,cm^{-3}}$	[11, 5]
Field capacity	θ_{fc}	0.30	$\mathrm{cm^3\,cm^{-3}}$	[11, 1]
Wilting point	θ_{wp}	0.15	$\mathrm{cm^3\,cm^{-3}}$	[11, 1]
Residual water content	θ_r	0.06	$\mathrm{cm^3\,cm^{-3}}$	[4]
Initial water content	θ_0	0.30	$\mathrm{cm^3\,cm^{-3}}$	Measured data
Drainage rate (bucket)	D	2.0	$\mathrm{mm\,day^{-1}}$	[1, 5]
Root-zone depth	z	35	cm	[1]
Solar radiation	R_s	data-based	$\mathrm{cal\,cm^{-2}\,day^{-1}}$	[12]
Mean air temperature	T	data-based	°C	[12]

4 Results

4.1 Visual outputs

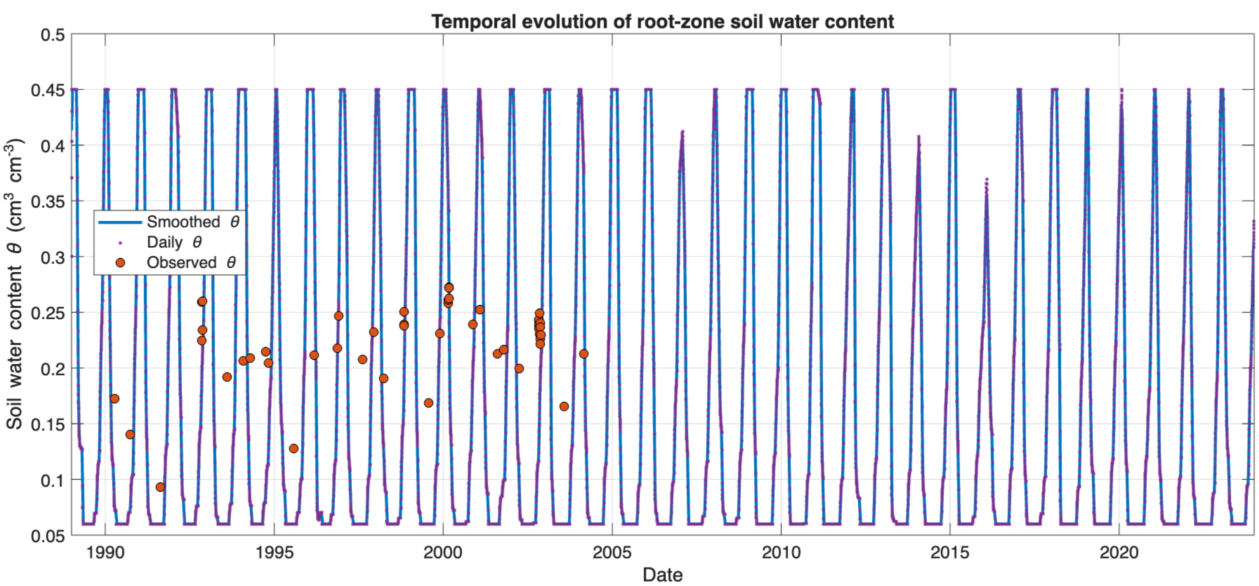

Figure 1: Seasonal fluctuation of SWC : 1989-2024

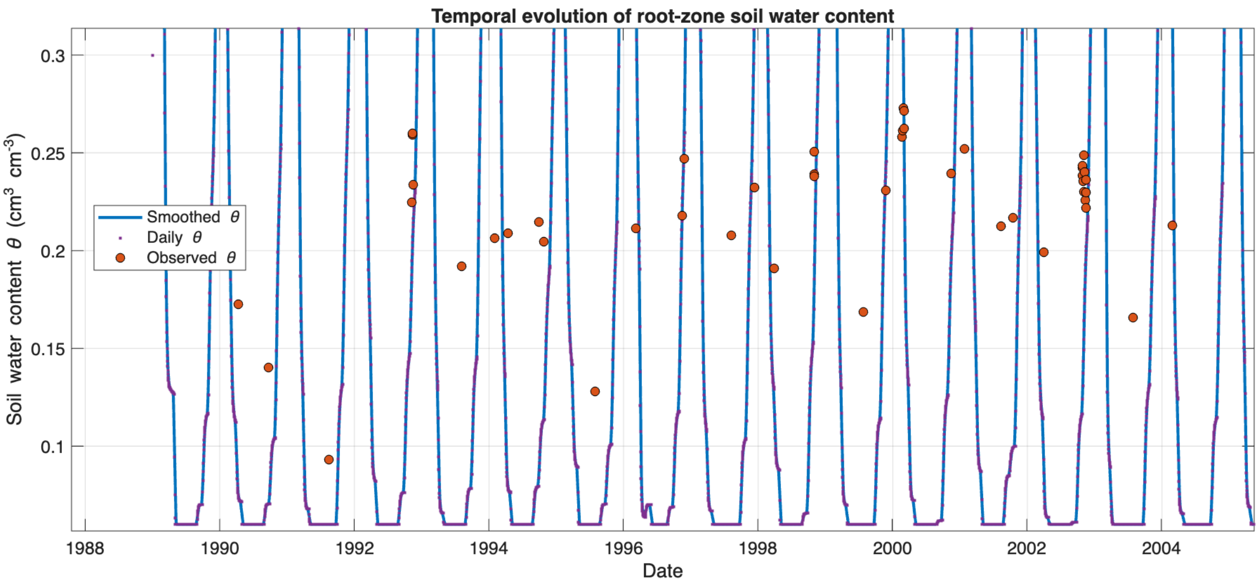

Figure 2: Seasonal fluctuation of SWC : zoom at the research time scale

The temporal evolution of root-zone soil water content θ exhibits a pronounced seasonal cycle with an approximately annual period, characterized by wetter conditions in winter and drier conditions in summer. The simulated SWC follows a sinusoidal-like pattern bounded by values corresponding to saturated and residual soil water contents. Both the daily and smoothed model outputs display extended plateaus at these upper and lower bounds. Comparison with observed soil water content shows a generally good agreement for intermediate moisture levels (approximately 0.15–0.30), where most observations are concentrated. The observed data indicate seasonal variability consistent with the modeled signal, as well as interannual differences in peak amplitudes, with some years (e.g., around 2006, 2014, and 2016) exhibiting reduced maxima.

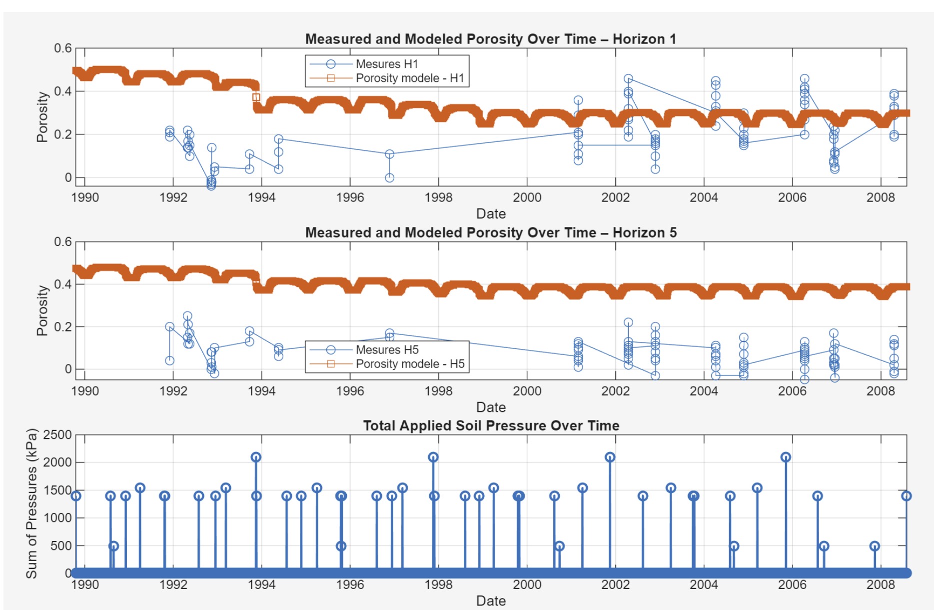

Figure 3: model vs observed porosity and days of interventions

The results of the porosity model appear above3 with the model in orange, plotted over the observed value and a accessory graph of the sum of the applied pressure per day (intervention). . Both the horizons show similar trend of successive parabolas. Over all the porosity decreases with time and applied pressures. More over, this slope is rather steep at first but stabilizes and becomes the drops at the times of pressure application becomes less high with time. On the other hand, the observations by [7] (in blue) are quite scarce and no clear trend can be reliablx identified as the the repartition is rather chaotic. Another noticeable point is the difference between the 1st and 5th horizon of the soil. The 1st seems to have a more variable porosity as it decreases faster and takes more time to stabilize around 0.3 after 2004. Besides, the 5th horizon shows less clear decreasing behavior and stabilizes at a higher value somewhere between 0.35 and 0.4 after 2000. Finally the observations and the model tend to align after the year 2000 for the 1st horizon but the model remains higher than the observation during all the period of interest.

4.2 Discussion

The presence of flat plateaus at the upper and lower bounds of simulated θ suggests that soil moisture dynamics in the model are partially constrained by imposed boundaries, indicating a degree of artificial forcing. Such abrupt transitions are unlikely to fully represent real soil water processes, which are typically smoother and governed by gradual changes in infiltration, drainage, and evapotranspiration.

The agreement between modeled and observed soil water content at intermediate values indicates that the model performs reasonably well under typical moisture conditions. However, the limited number of observations at very high and very low θ values restricts the evaluation of model performance at extreme conditions. This limitation may be explained by the measurement protocol described by cite{Lamichhane2021}, which reports that soil moisture measurements were conducted primarily during periods of agricultural machinery operation. As such activities are generally avoided during wet conditions to prevent soil compaction, higher soil water contents may be underrepresented in the observational dataset.

Additionally, the frequent simulation of very low summer soil water contents, in some cases approaching or falling below the wilting point, suggests that the model may have a tendency to overestimate soil drying. This behavior could contribute to the reduced peak amplitudes observed in certain years and highlights the potential impact of simplifying assumptions in the model formulation, particularly near extreme moisture conditions.

The main interpretations drawn from Fig. 3 are the following. Porosity decrease is clearly correlated with high-pressure events, supporting the assumption that soil compaction is primarily driven by agricultural machinery traffic. The magnitude of these porosity drops tends to decrease with successive interventions, suggesting a progressive saturation of compaction and indicating that the soil becomes less sensitive to further mechanical stress beyond a certain compaction level.

Additionally, the curve corresponding to the fifth horizon exhibits a lower sensitivity to compaction. This behavior can be explained by the attenuation of applied stresses with depth: pressure propagates through the soil profile and is therefore less intense when reaching deeper layers, resulting in smaller porosity variations.

Finally, the parabolic patterns observed in the temporal evolution of porosity are most likely driven by the dependence of bulk density on soil water content. As soil moisture follows a seasonal cycle, the computed porosity consequently exhibits a corresponding annual oscillation.

5 Conclusion and outlook

This project provided an opportunity to apply the theoretical tools introduced during the course to a real environmental problem related to soil functioning under agricultural use. The main objective was to simulate the temporal evolution of soil water content and soil porosity in order to assess the impact of agricultural machinery on soil health.

The modeling results show that the soil water content simulation captures the main seasonal dynamics and provides coherent estimates for intermediate moisture conditions, where most observational data are available. However, the model behavior at extreme moisture values remains uncertain, as the imposed bounds and simplified process representations may not fully reflect real soil water dynamics. Similarly, the porosity model reproduces theoretically consistent trends, such as porosity decreases associated with machinery traffic and a reduced sensitivity after repeated interventions. Nonetheless, the limited and irregular distribution of observational data prevents a robust quantitative validation of these results and makes the strength of the inferred correlations debatable.

Several difficulties were encountered during the project. The structure and clarity of the reference dataset required extensive preprocessing, resulting in a workflow that is highly specific to the studied site and limits the generality of the implementation. In addition, the automation of interactions between MATLAB and C programs introduced technical complexity, increasing the overall rigidity of the code structure.

Future work could address these limitations by incorporating a broader range of observations to improve model calibration and validation, particularly under extreme soil moisture conditions. Including biological factors, such as soil fauna activity, would allow for a more realistic representation of soil structure evolution. Improvements to the water content model could also be achieved by integrating soil texture–specific hydraulic properties rather than relying on empirical parameter choices. Finally, refactoring the code to reduce redundancy and enhance modularity would improve its robustness and facilitate application to other study sites.

6 (contributions of each student on the team to the project)

Flora :

- searching of the imputs data ([7]) and extraction of the value of interest (matlab)
- agricultural machinery sorting
- soil porosity modelling

Mathilde :

- Hydrological processes research + modeling
- Writing of the report
- Automation

7 References

References

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