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# Evaluation of pedotransfer-functions for soil indicators of BLN

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Reference

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Report

This study collected and evaluated existing pedo transfer functions (PTFs) for soil indicators used in the Dutch BLN soil quality assessment framework. The tested soil parameters include bulk density, plant available water, water holding capacity, hot water carbon and potentially mineralizable nitrogen. The PTFs are analysed for their consistency, uncertainty, and applicability to different settings. Although the variations among PTFs are large, the required input parameters and how those parameters influence the predicted value are generally similar. It is important to carefully select a PTF that match the domain of the applied context. Soil PTFs are useful for comparison of soil parameters across fields, farms and regions but insensitive to temporal changes within a field.

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# Content

# Summary

Soil indicators are needed to access the quality of soils. In Netherlands, an indicator set called BLN (‘*Bodemindicatoren voor Landbouwgronden in Nederland*’) was developed to integrally evaluate the quality of agricultural soils. BLN has been applied and tested in various projects. Quantifying BLN indicators often requires labour-intensive measurements, limiting their on-farm use. An alternative might be to include methods to estimate those difficult-to-measure parameters by so called pedotransferfunctions (PTFs), being empirical relationships calibrated on large datasets. The use of PTF’s helps the application of BLN on a much larger spatial scale at lower cost.

This study collected existing PTFs for BLN indicators using a literature survey. The collected PTFs were tested with 1000 randomly selected Dutch agricultural fields. About 181 PTFs were collected for bulk density, 16 for plant available water, and 10 for potentially mineralizable nitrogen (PMN). In addition, a single PTF was derived for Hot Water Carbon (HWC) from observations done in historical research projects. Although the variation is large in terms of the required input parameters and how those parameters influence the predicted value, there are many similarities among PTFs.

Our small exercise with Dutch agricultural soils showed that the predicted indicator values vary largely among PTFs. Some PTFs yield unrealistic values, especially when the type of soils on which the PTF is based do not match that of the soils examined. So, for all indicators, it is important to carefully select PTFs that match the domain of the applied context. Nevertheless, changes in indicator values are usually consistent, allowing broad application for farm, regional and national monitoring, whereas the absolute changes are difficult to assess or limited in magnitude due to the uncertainty in input parameters. This might limit their use on monitoring soil quality on field level over time, in particular for indicators reflecting the biological activity of soils such as HWC or PMN.

# 1. Introduction

### Background

Soil quality is an important basis for many ecosystem functions, such as food production, improving water quality, mitigating climate change and maintenance of biodiversity. In Netherlands, a framework was developed to holistically evaluate the quality of agricultural soils, abbreviated as BLN (‘*Bodemindicatoren voor Landbouwgronden in Nederland*’). BLN is a scientifically sound indicator set that forms the basis for determining the quality of Dutch agricultural soils for different land use objectives. The indicator set contributes to the ambition of the National Agricultural Soils Program that by 2030 all agricultural soils will be sustainably managed. BLN was applied and tested in various projects, such as ‘*PPS Beter Bodembeheer*’ and the research program ‘*Slim Landgebruik*’.

Currently, BLN version 1.1 is available (Figure 1) including 21 indicators (de Haan et al., 2021), whereas the updated BLN version 2.0 is available since summer 2023 (Ros et al., 2023a).

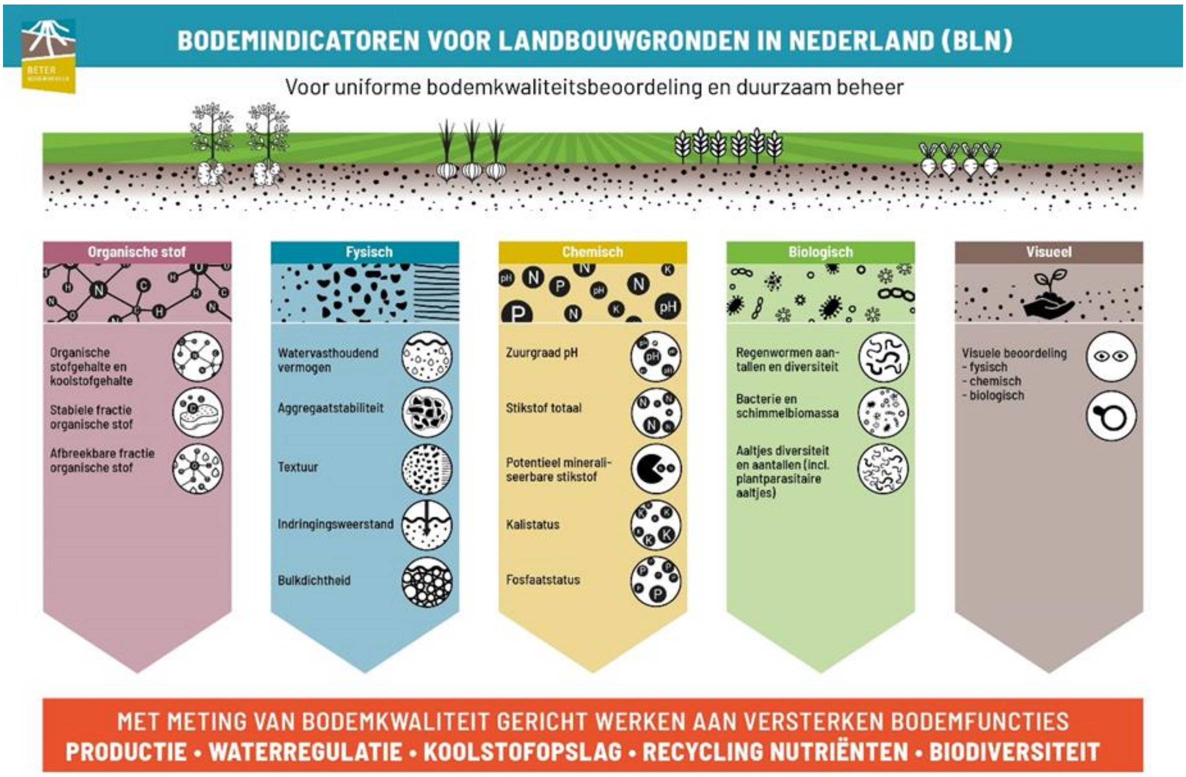


*Figure 1. Soil indicators of BLN v1.1. Source: (de Haan et al., 2021).*

The BLN requires a number of input values of field and soil properties. Those values can be obtained from field and laboratory measurements. Instead of the labour-intensive measurements, some difficult-to-measure parameters can also be estimated using empirical relationships (so-called pedotransfer functions, PTFs) based on more easily accessible parameters. The use of PTFs helps the application of BLN on a much larger spatial scale at lower cost.

This study aims at collecting existing PTFs for a series of BLN indicators based on literature survey. The collected PTFs are analysed for their consistency, uncertainty, and applicability to different settings.

### Approach

Pedotransfer functions of BLN indicators were searched in existing literature. The collected PTFs were scripted with R language and developed as an open source R-package called 'soilptf' (Ros et al., 2023b). We collected PTFs to estimate the following soil properties or indicators:

- Bulk density
- Plant available water and the water holding capacity
- The potentially mineralizable nitrogen pool
- The hot water carbon fraction

Note that the R package has been further developed during 2023 and that this report evaluates a snapshot of the functions collected. The soilptf package has additional PTFs for CEC (n = 81), the pH buffer capacity (n = 8), the mean weight diameter (n = 16), the percentage water stable aggregates ( n = 16), the threshold velocity as an index for the sensitivity for wind erosion (n = 3), and the metal availability in soil solution (n = 4).

The six aforementioned PTFs were tested with 1000 randomly selected Dutch agricultural fields to evaluate their variation across the land uses and soil types. Note that these PTFs were not evaluated on an independent set with observed BLN indicators determined via classic methods. The predicted BLN values were compared between PTFs and its uncertainty was discussed as well as their use in soil quality assessments on farm, regional or national scale.

# 2. Literature survey

## 2.1 Bulk density

Soil bulk density is one of the most important soil properties. On the one hand, it describes the quality of the soil since soil bulk density directly reflects soil porosity and compaction which influence water and air soil properties. On the other hand, soil bulk density is a crucial parameter used in balancing and modelling of various processes in the environment. Soil bulk density can be determined in two ways: directly in laboratory using core samples by a thermogravimetric method and indirectly using prediction methods including the use of PTFs which are equations or algorithms representing relationships between soil properties different in difficulty of their measurement or their availability. PTFs use thereby other parameters of soil to estimate its bulk density such as soil organic matter, soil organic carbon, and soil mineralogy (clay, sand or silt content).

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A number of PTFs exists to estimate soil bulk density. Of 181 collected PTFs, more than half of the PTFs were built on data of Europe (39%) or North America (19%). Some PTFs are built on data of specific land use type, such as forest (23%), nature (3%) or agriculture (11%). More than half of the PTFs require only 1 input parameter (54%), followed by 2 parameters (20 %) and 3 parameters (16 %). Almost all PTFs use soil organic matter or soil organic carbon as input parameter, and many also use soil minerology (e.g. sand and clay content) as additional input parameters (

Table 1). More details of these ptfs as well as the associated literature can be found in Ros et al. (2023b).

*Table 1. Input parameters used in 181 PTFs for bulk density.*

| Parameter | Number of PTF | % |
|---|---|---|
| organic C | 104 | 57.5 |
| SOM | 68 | 37.6 |
| clay | 60 | 33.1 |
| sand | 36 | 19.9 |
| silt | 30 | 16.6 |
| depth | 17 | 9.4 |
| pH | 8 | 4.4 |
| slope_degree | 4 | 2.2 |
| $CaCO_3$ | 3 | 1.7 |
| altitude | 2 | 1.1 |
| total nitrogen | 2 | 1.1 |
| volumetric water content | 2 | 1.1 |
| slope_aspect | 1 | 0.6 |

** more details for each PTF can be found online.*

## 2.2 Plant available water and Water holding capacity

Availability of water for plant can be expressed with several parameters, such as plant available water (PAW: maximum amount of water that soil can store to be extracted by plants) and water holding capacity (WHC: amount of water when all soil pores are filled with water). The PAW of a soil can be calculated from the soil water retention curve, as the difference in volumetric water content between field capacity and wilting point. WHC of a soil is equivalent to the volumetric water at saturation. The parameters of soil retention curve are indispensable for most hydrological models and can be measured with e.g. wetting experiment in sand box, yet the measurements are time and labour intensive. Therefore, many PTFs have been developed to estimate the soil water retention parameters based on more easily measurable soil parameters such as minerology and organic matter.

There are mainly four types of PTF to estimate soil water retention parameters. The first type uses look-up tables listing average parameters in each texture class (class PTFs, (sensu Nasta et al., 2021)). The second type (point PTFs) estimates soil water contents at fixed matric head values, such as field capacity and wilting points. The third type (semi-physical PTFs) comprises physically sound (but semi-empirical) models based on the assumption of shape similarity between the particle-size distribution and pore-size distribution. The fourth type (parameter PTFs) is based on the data-driven estimation of parameters with multiple regression equation or more complex machine-learning approaches.

Extensive review of different PTFs can be found elsewhere. For example, Nasta et al. (2021) tested eleven PTFs to estimate water retention using three large dataset of European soil samples. Three recent PTFs (Szabó et al., 2021; Weynants et al., 2009; Wösten et al., 1999), all using van Genuchten retention curve, proved to be accurate enough to predict water retention of the wide variety of the soils. Another review of PTFs by Vereecken (2010) showed that soil organic matter is an important predictor for water retention, especially in the wet and dry ranges. Although there have been attempts to omit organic matter (or organic carbon) due to its strong correlation with bulk density, the inclusion of both bulk density and organic matter in the PTF can better represent the dynamic character of soils because bulk density is strongly influenced by other factors such as management practices and drainage (Van Looy et al., 2017).

In this study, 16 existing PTFs to estimate PAW and WHC were collected (see Table 4 in Appendix for overview). All PTFs requires clay content as an input parameter (Table 2).

*Table 2. Input parameters used in 16 PTFs for PAW and WHC.*

| Parameter | Number of PTF | % |
|---|---|---|
| clay | 16 | 100 |
| sand | 10 | 63 |
| bulk density | 9 | 56 |
| silt | 8 | 50 |
| organic C | 6 | 38 |
| SOM | 5 | 31 |
| topsoil (true or false) | 3 | 19 |
| sand median size (um) | 3 | 19 |
| depth | 2 | 13 |

** more details for each PTF can be found online.*

Furthermore, all PTFs requires either bulk density, soil organic matter or soil organic C (or combination of some of them) as input parameters. It includes 1 class-PTF, 4 point-PTFs, 2 semi-physical PTFs, and 9 parameter PTFs. 10 out of the 16 PTFs can also be used to estimate WHC.

## 2.3 Potentially mineralizable-N

The potential of soils to supply N is usually measured with biological assays of soils. Biological assays estimate mineralizable N from gross or net increases in inorganic N during incubation from potential pools or rates calculated from long-term incubation, or from N uptake by plants grown in greenhouse or field experiments. These biological methods are considered to be the most reliable estimators but they are expensive, time-consuming and labour-intensive and their results strongly depend on experimental conditions.

When the mineralizable N pool has been estimated from long-term laboratory incubations (time scale 0.5 to 3 years), it is often called potentially mineralizable N, bioavailable N or N supplying capacity (Nannipieri & Eldor, 2009; Stanford & Smith, 1962). This potentially mineralizable N pool is usually estimated along with its mineralization rate constant using a first order exponential function. The fraction that mineralizes in short-term laboratory incubations and field experiments (time scale 1 to 4 weeks) is often called net N mineralization or (actual) mineralizable N (Ros, 2011). For example, a widely adopted approach is the short-term anaerobic incubation quantifying the ammonium released from microbes killed by the anoxic condition in a soil-water mixture incubated for 7 up to 14 days. The difference between both approaches is that the potentially mineralizable N pool reflects the amount of organic N that can be mineralized (no environmental constraints) whereas the actual mineralizable N pool is the fraction that actually mineralizes (depending on environmental conditions).

The so-called (potentially) mineralizable nitrogen (PMN) gives insight into the microbial activity in soils and the quality of the soil organic matter with respect to its potential to supply nitrogen throughout the growing seasons. Since PMN is a time-consuming measurement, a number of pedo transfer functions have been developed. In this study, we collected 10 PTFs from literature (see Table 5 in Appendix for overview). Total N and organic C are the most frequently used input parameters: 4 PTFs use both, 1 PTF uses organic C only, and 5 PTFs use total N only (Table 3). Of 10 PTFs, about 3 were obtained by a linear regression model of measured PMN regressed by several soil properties. The other 7 PTFs were built to estimate parameters describing the release of N via first order kinetics or a combination of zero order and first order kinetics. The prediction function for PMN using first pool kinetics is written as:

$$N_t = N_0[1 - exp(-k_0 t)]$$

where $N_t$ is the mineralized N for time *t*, $N_0$ it the potentially mineralizable N pool (mg N kg$^{-1}$), $k_0$ is the first order rate constant, *t* is the incubation time (week).

The prediction of PMN using 2-pool kinetics is written as:

$$N_t = N_1[1 - exp(-k_1 t)] + N_r[1 - exp(-k_r t)]$$

where $N_1$ and $N_r$ are the amount of organic N in labile and resistant N pools, $k_1$ and $k_r$ are the corresponding first order rate constants for those N pools.

About four PTFs were built on anaerobic incubation data, whereas the rest were on aerobic incubation data (usually with moderate moisture condition). The incubation conditions also differed among studies in terms of incubation temperature and incubation period. An analysis with global dataset revealed that the temperature has limited effects on PMN, whereas a longer incubation period leads to an increased PMN (Ros & Fujita, 2020). Therefore, the estimated PMN by different PTFs were converted to the PMN for a standard length of incubation period, 7 days, using an empirical relationship (n = 315, P < 0.001) as follows:

$$PMN_{cor} = PMN \cdot \frac{b0 + b1 \cdot \ln(7)}{b0 + b1 \cdot \ln(d)}$$

where *PMN_cor* is the PMN corrected for 7 days (mg N kg$^{-1}$), *d* is the incubation time (day), PMN is the original PMN measured for *d* days (mg N kg$^{-1}$), and *b0* and *b1* are regression coefficients (*b0* = 2.495, *b1* = 0.5131).

*Table 3. Input parameters used in 10 PTFs for PMN.*

| parameter | Number of PTF | % |
|---|---|---|
| total N | 9 | 90 |
| organic C | 5 | 50 |
| clay | 5 | 50 |
| silt | 3 | 30 |
| CEC | 3 | 30 |
| pH | 3 | 30 |
| Fe_DTPA | 1 | 10 |
| cultivated (T/F) | 1 | 10 |
| residue (T/F) | 1 | 10 |

## 2.4 Hot Water Carbon

The hot water extractable carbon pool has been used in various studies to represent a labile carbon pool responsive to changes in soil, crop and fertilizer management. Compared to other indicators, HWC is frequently linked to soil biological properties while being sensitive to both tillage and organic matter addition. As such it might be an informative indicator to evaluate changes in soil quality. Since the biological activity in a soil increases with the total soil organic matter, there is often a strong relationship between total SOM and measured levels of HWC. As a consequence, differences in HWC due to management can be monitored and evaluated across soils having comparable SOM levels, otherwise the impact of management is confounded by the differences in SOM. This suggests that the relative contribution of HWC to the total levels of Carbon in soil are more robust indicator for soil quality that the HWC level itself. Similar findings have been observed for almost all extractable soil organic carbon fractions (Ros, 2011).

Using 1024 observations from various studies done in the Netherlands during last decade confirms that the levels of HWC are positively and strongly correlated to the levels of SOM (Figure 2). Part of the uncertainty can be removed by using soil organic C (determined as C-kurmisch) given the lab uncertainty of the classical loss-on-ignition method used for SOM. The data used originated from the project "Zorg voor Zand" (Van Eekeren, 2006), the public-private-partnership for Beter Bodembeheer, projects for "Slim Landgebruik" including long-term experiments in the Netherlands (Koopmans & Bloem, 2018; Hoogmoed et al., 2021), and the PhD projects of Nick van Eekeren (Van Eekeren, 2010), Joachim Deru (Deru, 2022) and Ros (Ros, 2011). It includes observations across all relevant land uses, soil types and management practices in the Netherlands.

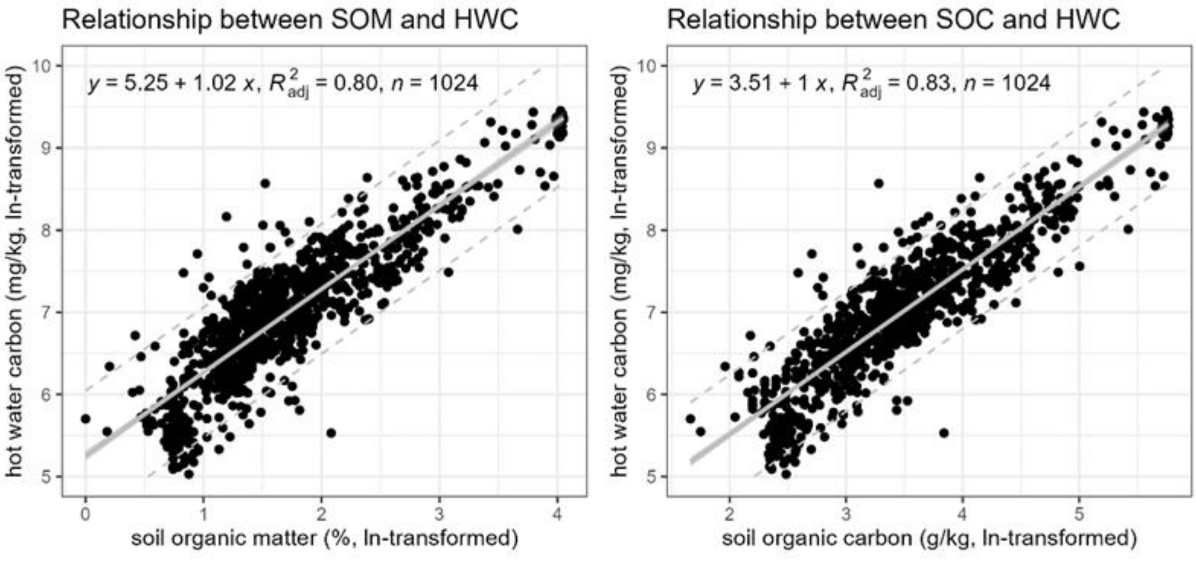



*Figure 2. Relationship between HWC and SOM (left) and SOC (right).*

When analysing the relative contribution of HWC to total carbon, then it becomes clear that on average 3.6% of the total carbon is present in the soil as hot water carbon fraction. The fraction of HWC over total C has a relatively small range, with 90% of the observations varying between 2.2 and 5.2%, and 95% between 1.9 and 6.1% (Figure 3).

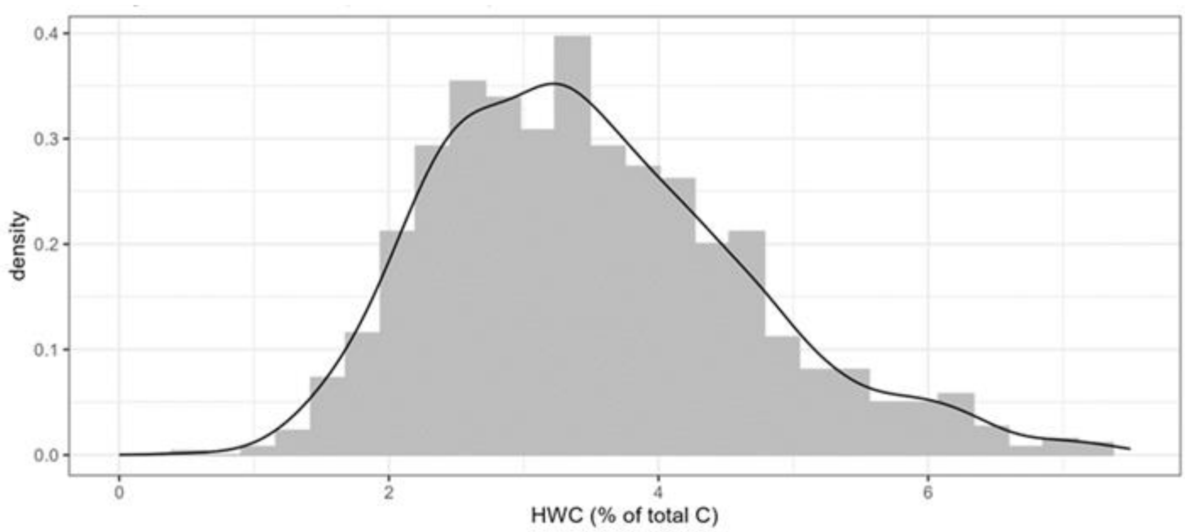



*Figure 3. The relative contribution of HWC tot total C for 1024 samples.*

The small variability (and the fact that land use or management had on average no significant impact on the HWC fraction of total C) was surprising given the fact that observations have been derived from various studies including multiple land uses (maize, bulbs, grasslands, potatoes), soil types (peat, clay, sand, loam), and a high variation of management practices (ploughing and no-till, catch crops included or not, high compost doses and inorganic fertilizers only, variable types of animal manures). This suggests that the interpretation of relative changes in HWC are highly site specific, challenging its use in national soil quality monitoring.

The averaged HWC as a function of total C can be predicted via:

$$C_{hw} = \exp\left(3.508 + 1.004 * \ln\left(C_{tot}\right)\right)$$

where $C_{hw}$ is the concentration of hot water extractable carbon (mg $kg^{-1}$), and $C_{tot}$ is the total carbon level (g $kg^{-1}$) in soil.

This PTF can be used to estimate the HWC concentration when total C levels are known. Note that the use of this generic PTF is not applicable to monitor and assess changes due to management measures independent of their impact on total C. It might help for evaluating soil quality on farm level (differentiating differences among fields), regions (e.g. showing differences between land uses, soil types) and national level (e.g. showing differences across regions), but application of this PTF on field level (to monitor changes due to management) should be avoided.

## 2.5 Other BLN indicators

There exist PTFs for other BLN indicators, such as aggregate stability (Saidi et al., 2015), P saturation (Kleinman et al., 1999), available P (Hu et al., 2020; Khaledian et al., 2018), carbon pools (Weihermüller et al., 2013; Zimmermann et al., 2007), and CEC (Chakraborty et al., 2020; McBratney et al., 2002). Due to limited number of available PTFs, no analysis was made for these indicators in this study.

The soilptf package has additional PTFs for CEC (n = 81), the pH buffer capacity (n = 8), the mean weight diameter (n = 16), the percentage water stable aggregates ( n = 16), the threshold velocity as an index for the sensitivity for wind erosion (n = 3), and the metal availability in soil solution (n = 4).

## 2.6 Assembling different PTFs

As many PTFs have been developed, the next crucial step is to assemble those different PTFs efficiently. An example of such an attempt is made by Guber et al. (2009), who combined 19 published PTFs of water flow equation using a multimodel prediction technique, to obtain more reliable predictions. Another example is the soil inference system (SINFERS) approach advocated by McBratney et al (2002). This method matches the available input with the most appropriate PTF to predict properties with the lowest uncertainty. The output of one PTF can act as the input to others, while tracking propagation of uncertainty. In this way, one can chain PTF predictions together while accounting for uncertainty.

In our R-package 'soilptf', we tentatively chose a simple method to use a median value predicted with all relevant PTFs. A relevant PTF means that the PTF was developed for the same region and same land use type, or the PTF is developed for non-specific settings. In future, more sophisticated method to assemble values predicted by different PTFs can be adopted.

# 3. Comparison among PTFs

To compare different PTFs, a test set was created by randomly selecting 1000 fields with varying soil properties from a large dataset of all Dutch agricultural soils. This test set includes various soil type and land use types (Figure 4). The test set was used to evaluate the predicted bulk density, plant available water, water holding capacity, potentially mineralizable nitrogen and hot water carbon with different PTFs, assuming that these 1000 soils are a representative set of all Dutch agricultural soils.

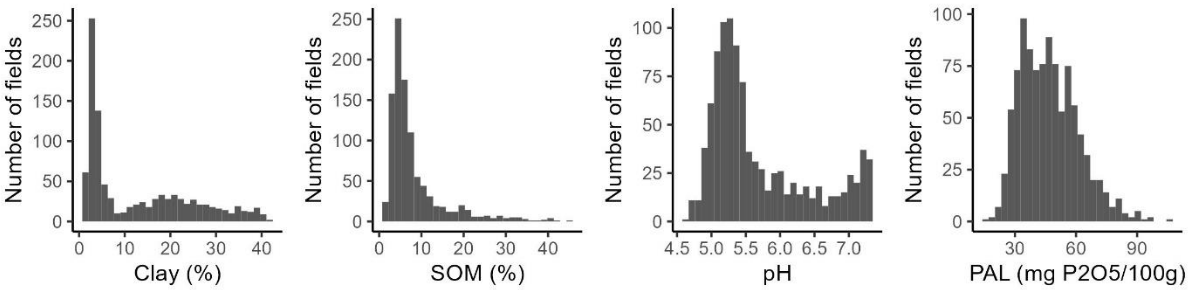
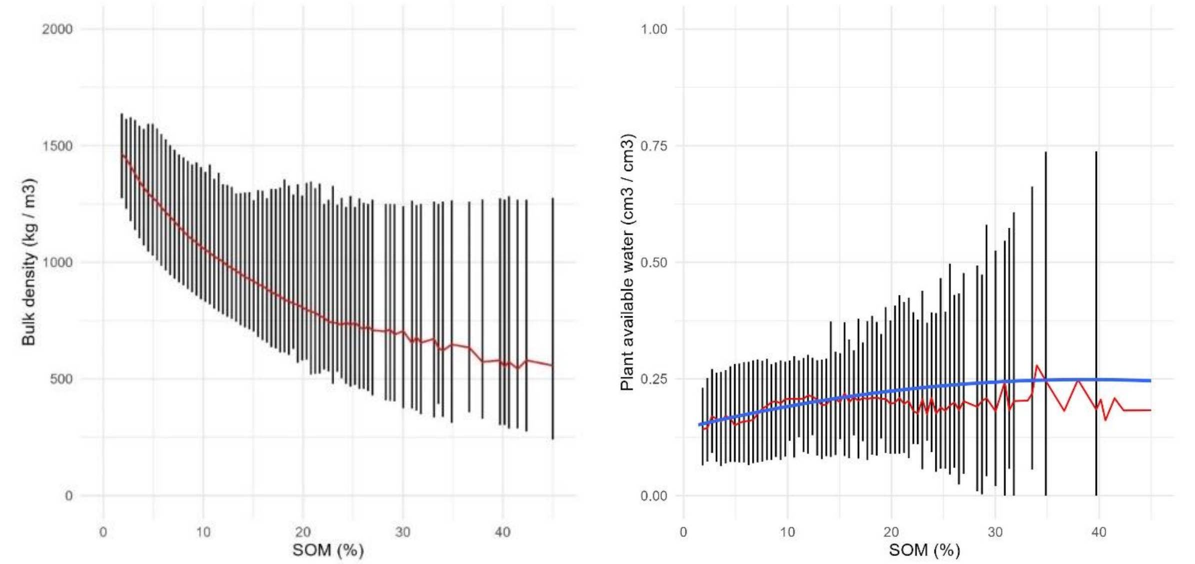



*Figure 4. frequency distribution of clay, soil organic matter content, pH, and PAL (ammonium lactate extractable P) of 1000 fields of the test set.*

## 3.1 Variation in predicted indicators

The estimated indicator values varied by the choice of the PTF as well the variation in soil properties. Below the patterns and causes of the variations are discussed for each indicator separately.



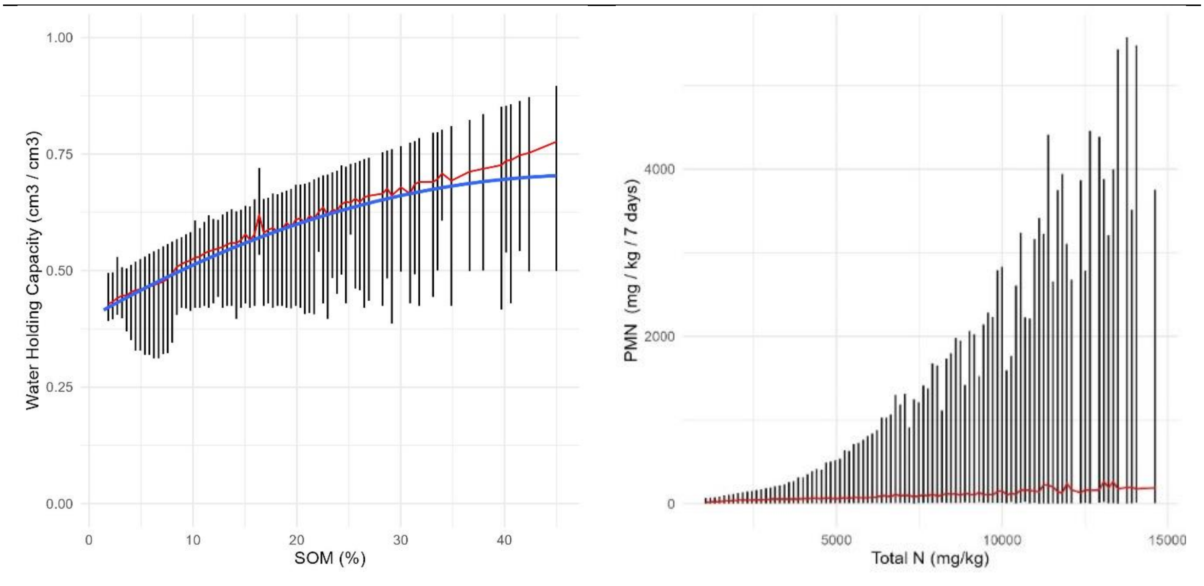



*Figure 5. Relationships between soil organic matter (%) and bulk density (kg $m^{-3}$) predicted with 59 pedotransfer functions (top-left), between soil organic matter (%) and plant available water ($cm^3$ $m^{-3}$) predicted with 14 pedotransfer functions (top-right), between soil organic matter (%) and water holding capacity ($cm^3$ $m^{-3}$) predicted with 10 pedotransfer functions (bottom-left), and between soil total N (mg $kg^{-1}$) and potentially mineralizable N (mg/kg/7 days) predicted with 10 pedotransfer functions (bottom-right), for 1000 randomly selected Dutch agricultural soils. The 1000 soils were split info 100 intervals of SOM or total N, and the variation of the predicted values ($5^{th}$ to $95^{th}$ percentile) are shown as vertical bars. Red line shows the median values, and blue line show the fitted model.*

### Bulk density

Of 181 PTFs of bulk density, 101 PTFs are built for outside Europe. Of the remaining 80 PTFs, 47 PTFs were built for forest or nature soils. Excluding those, 58 PTFs are left the further analysis. Of the 58 relevant PTFs, the predicted range of bulk density values in relation to SOM is rather confined (Figure 5 top-left), showing the typical relationship of gradually decreasing bulk density with increasing SOM. Estimated bulk density with not-relevant PTFs (e.g. PTF built outside Europe, built for forest soils; grey points in Figure 6 left in Appendix) often spans unrealistic ranges, highlighting the importance of careful selection of PTFs that match the domain of the applied context. The fitting lines of the PTFs shows the behaviour of each PTF more clearly (Figure 6 right, Appendix). Variation of bulk density is large for organic rich soils, and there are a few PTFs which predict unrealistically high bulk density. These PTFs are probably built on input parameters which have different range than Dutch agricultural soils.

Approximately one-third of PTFs include mineralogy (sand/silt/clay) as one of the input parameters. The effect of mineralogy is not consistent among PTFs, but in general clay soils tend to have a slightly lower bulk density if SOM level is comparable (Figure 7 in Appendix).

Note that a single wrapper has been developed in the soilptf package that is able to select the most appropriate PTF given location, land use, and soiltype.

### Plant available water and water holding capacity

The test set of Dutch agricultural soil (n = 1000) was used to analyse different PTFs for PAW and WHC. Two out of 16 PTFs were excluded because of their unrealistic values. The bulk density, which was used as an input parameter for most PTFs, were calculated as median value of all PTFs for bulk density applicable for Dutch agricultural soils. In general, PAW increases with increasing SOM (or organic C), or with decreasing bulk density, yet the variation among PTF was very large (Figure 5, top right). This is in line with an earlier comparison study of PTFs to predict PAW for Dutch agricultural soils (Ros et al., 2013). Behaviour of each PTF is shown in *Figure 8* in the Appendix. The effect of clay content on PAW varies among PTFs. Some PTF behaves unrealistically for soils with high clay content, such as PTF2 and PTF6. PTF2 was built for calcareous soils and thus not applicable for a wide range of soil type. In the validation study with global soils, PTF6 turned out to predict PAW inaccurately for clay soil (Nasta et al., 2021).

The predicted PAW values vary depending on which PTF is used, and the magnitude of the influence of the choice of PTF differs among soils (Figure 9 in appendix). Organic rich soils tend to have high values of quartile coefficient of dispersion, (Q3 - Q1)/(Q3 + Q1), the measure to evaluate the variation. Soils with high clay content don't necessarily have high variation, as far as the SOM content is low. This indicates that choice of PTF has a large impact on the predicted PAW values especially for SOM rich soils.

The predicted WHC also increases with increasing SOM (Figure 5, bottom-left). The variation due to PTF is smaller than that for PAW. This reflect the fact that PAW is calculated by two estimates of soil water characteristics (i.e. volumetric water content at field capacity and wilting point), whereas WHC is estimated from one soil water characteristic (e.g. volumetric water content at saturation).

#### Potentially mineralizable Nitrogen

PMN was predicted for the test set of Dutch agricultural soils with 10 PTFs (Figure 5 bottom right). The PMN value was standardized for the incubation period of 7 days. The range of total N in the dataset of PTFs is usually low compared to Dutch soil, whose 95 percentile ranges between 1,116 and 11,688 mg N $kg^{-1}$. This results in higher uncertainty in the predicted PMN values for N-rich soils, as seen in unrealistically high PMN values for N rich soils predicted with PTF2. Also, the kinetics model (which were used for all PTFs except for PTF1, PTF3, PTF4) may be especially sensitive to the range of source dataset, because separately predicted 2 coefficient values (mineralizable pool N0 and mineralization rate k) are multiplied, resulting in errors propagating nonlinearly. Further, soils of PTF1 to PTF4 were incubated in an anaerobic condition, whereas those of other PTFs were incubated aerobically and often at lower temperature. The difference in the incubation conditions could have resulted in deviating values of PMN.

## 3.2 Use of PTF in soil quality assessments

Some of the soil parameters are more dynamic than the others. For example, soil texture usually does not change over time, whereas soil organic matter content can gradually change, typically in the time scale of decades, and soil moisture content fluctuate rapidly. Most of the input parameters for the PTFs are stable parameters. This means that the variability of soil indicators predicted with the PTFs are mainly reflecting the (spatial) variability of the stable parameters, being not sensitive to short-term impact of management. It can reflect changes of long time, or mean difference between locations. Thus, the PTF-derived soil indicators are applicable to compare fields, farms and regions, but not to examine short-term impacts of management on field level.

Be aware that the set of soil parameters used as input differ among PTFs. Therefore, the variation in the derived indicators reflect not only the variation in the input soil properties but also the choice of PTF. Thus, among-field comparison should be made based on a single PTF, or multiple PTFs if they are 'properly' aggregated. As discussed in section 2.6, assembling different PTFs is a crucial step to make use of knowledge and data behind many available PTFs. If multiple PTFs are aggregated properly, it may facilitate soil quality assessment more robustly than a single PTF.

# 4. Concluding remarks

There exist many PTFs to predict soil properties like bulk density, plant available water, and potentially mineralizable nitrogen. Although the variation is large in terms of the required input parameters and how those parameters influence the predicted value, there are many similarities among PTFs. Bulk density is always predicted from SOM or organic C, with more input parameters adding marginal tuning. A higher SOM or organic C is associated with a lower bulk density. Plant available water is predicted from clay, as well as SOM and/or organic C and/or bulk density. A higher SOM usually leads to higher plant available water, whereas the effect of mineralogy is not very consistent among PTFs. For potentially mineralizable nitrogen, total organic N and/or C is the necessary input parameters, with a higher organic N or C associated with higher PMN.

Our small exercise of different PTFs with Dutch agricultural soils showed that the predicted bulk density was rather consistent among PTFs, as far as not relevant PTFs (i.e. PTFs made for outside Europe, for forest, etc.) were excluded. Organic rich soils have relatively high uncertainty. The predicted plant available water has a large variety, especially for organic rich soils. Some PTFs give unrealistic ranges of values, especially when the type of soils on which the PTF is based do not match that of the soils examined. The predicted PMN had even higher uncertainty. This is mainly because most PTFs were developed for soils with much lower SOM content than Dutch agricultural soils.

Though a real validation of the collected PTFs with classic measurements would be preferred, we can still conclude that PTFs as such can be used to quantify the spatial variation in bulk densities, water retention properties, and biological indicators like Hot Water Carbon and Potentially Mineralizable Nitrogen. This is particularly true when the most relevant PTF is selected given land use, soil texture and region for which the PTF has been derived; the evaluation of all PTFs independent of these site properties might lead to undesired high uncertainty and even unreliable predictions (see examples in the Appendix). Given the nature of the PTFs (being estimated from rather constant soil properties) they are particularly useful for regional and national assessments whereas within field variation or temporal variation in soil quality indicators can not be quantified with the current PTFs.

For all indicators, it is important to carefully select PTFs that match the domain of the applied context. Furthermore, the trend of influence of input parameters on the predicted indicator values was usually consistent, but not the magnitude of the influence (especially for PAW and PMN). Therefore, when indicator values of multiple sites are compared, it is recommended to use a single PTF.

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# Appendix

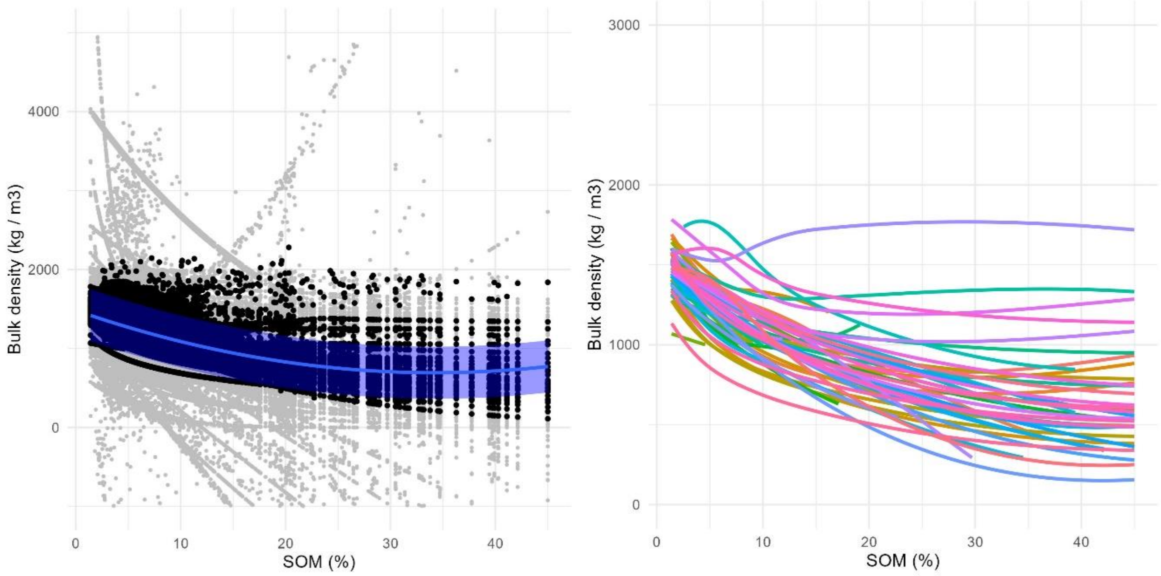


*Figure 6. Relationships between soil organic matter (%) and bulk density (kg/m3) estimated with different pedo transfer functions. Left: Black points shows the bulk density of 1000 data points of Dutch agricultural soil, predicted with 58 relevant PTFs. Blue line depicts the fitted line, with the purple band showing its 95% prediction interval. Grey points depict bulk density predicted with 122 not-relevant PTFs  Right: Fitted lines of 58 relevant PTFs.*

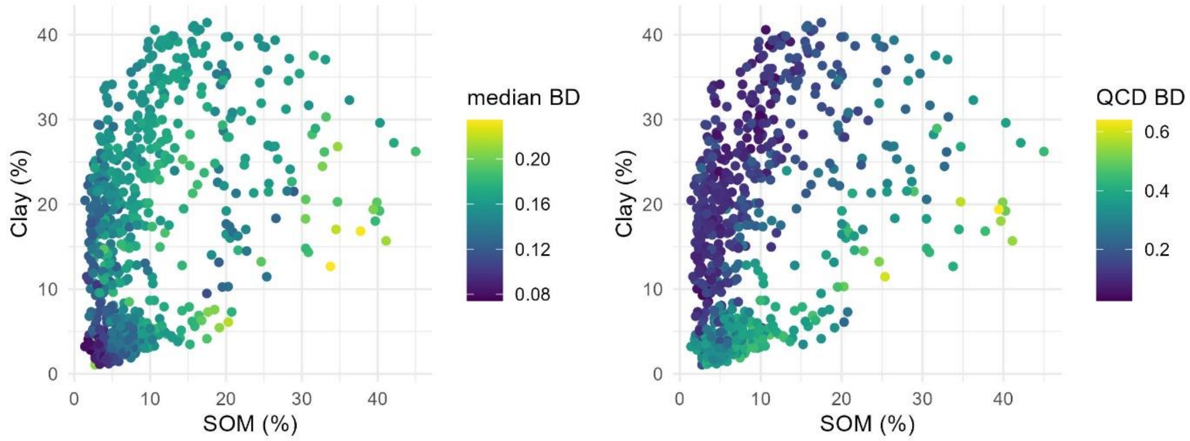


*Figure 7. Median value (left) and quartile coefficient of dispersion (QCD, right) of bulk density of 1000 Dutch agricultural fields, calculated with 58 relevant PTFs. A larger QCD means a larger variation in BD values among different PTFs.*

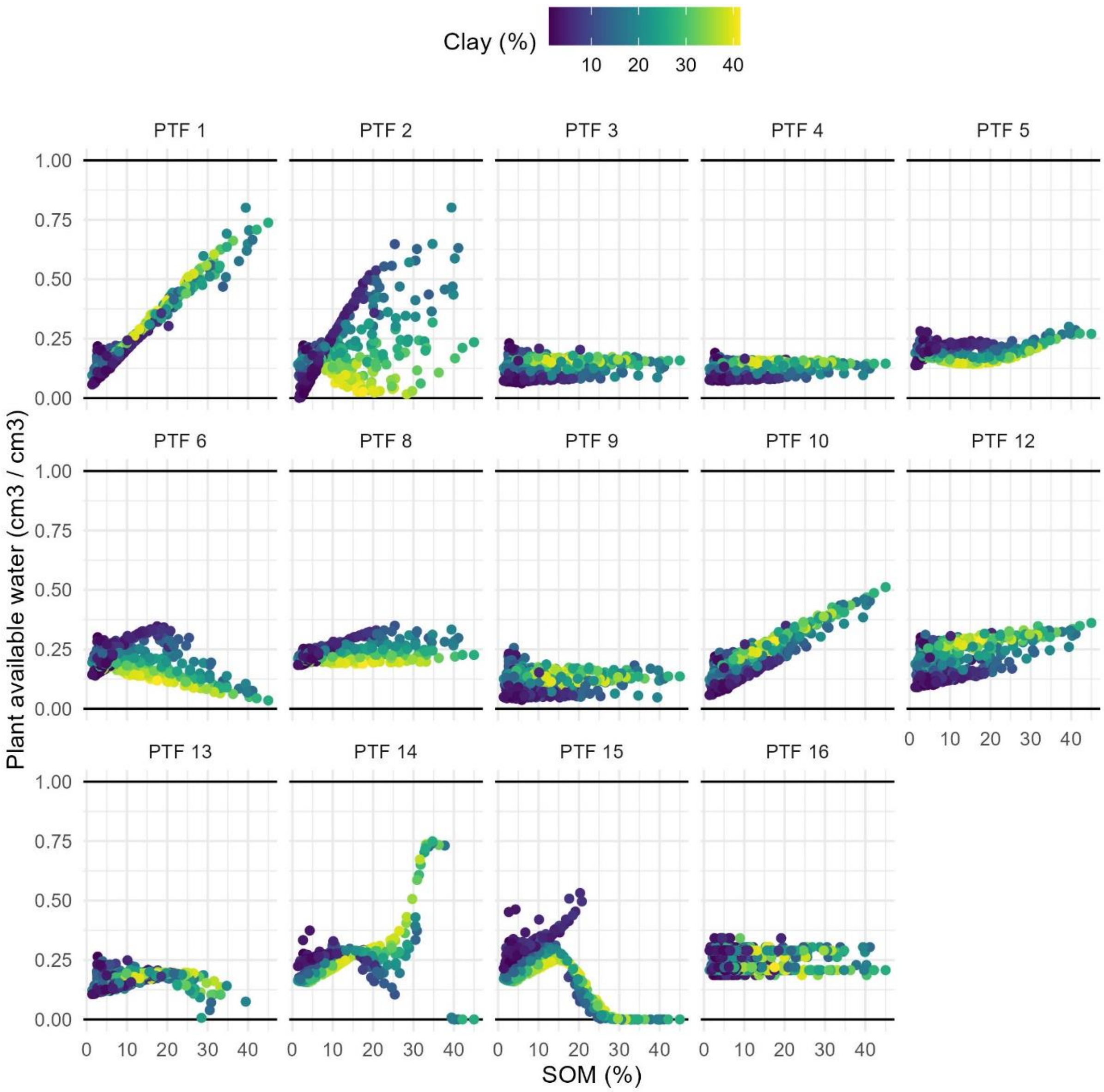


*Figure 8. Plant available water (PAW) estimated with 14 different PTFs for 1000 Dutch agricultural soils. PAW was calculated as the difference in volumetric water content at field capacity (33 kPa) and wilting point (1500 kPa). Color depicts clay content. Negative PAW values are invalid.*

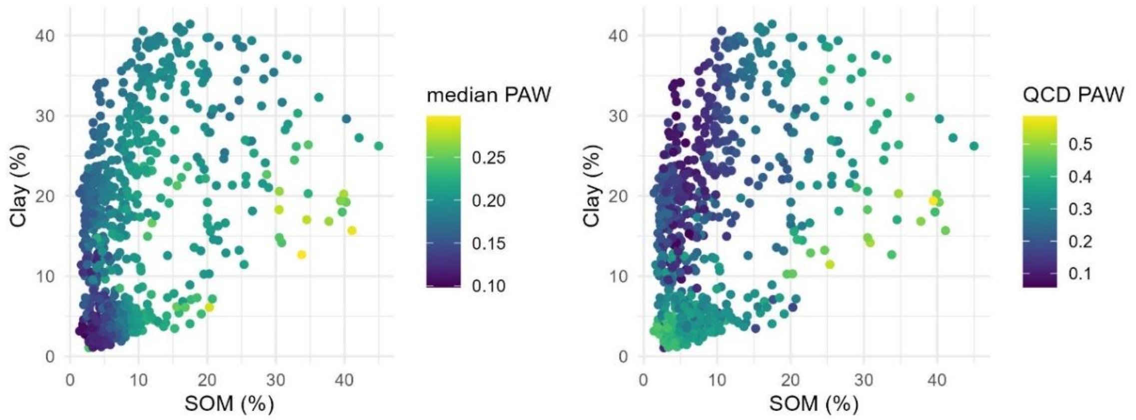


*Figure 9. Median value (cm$^3$ cm$^{-3}$, left) and quartile coefficient of dispersion (QCD, right) of plant available water of 1000 Dutch agricultural fields, calculated with 14 PTFs. A larger QCD means a larger variation in PAW values among different PTFs.*

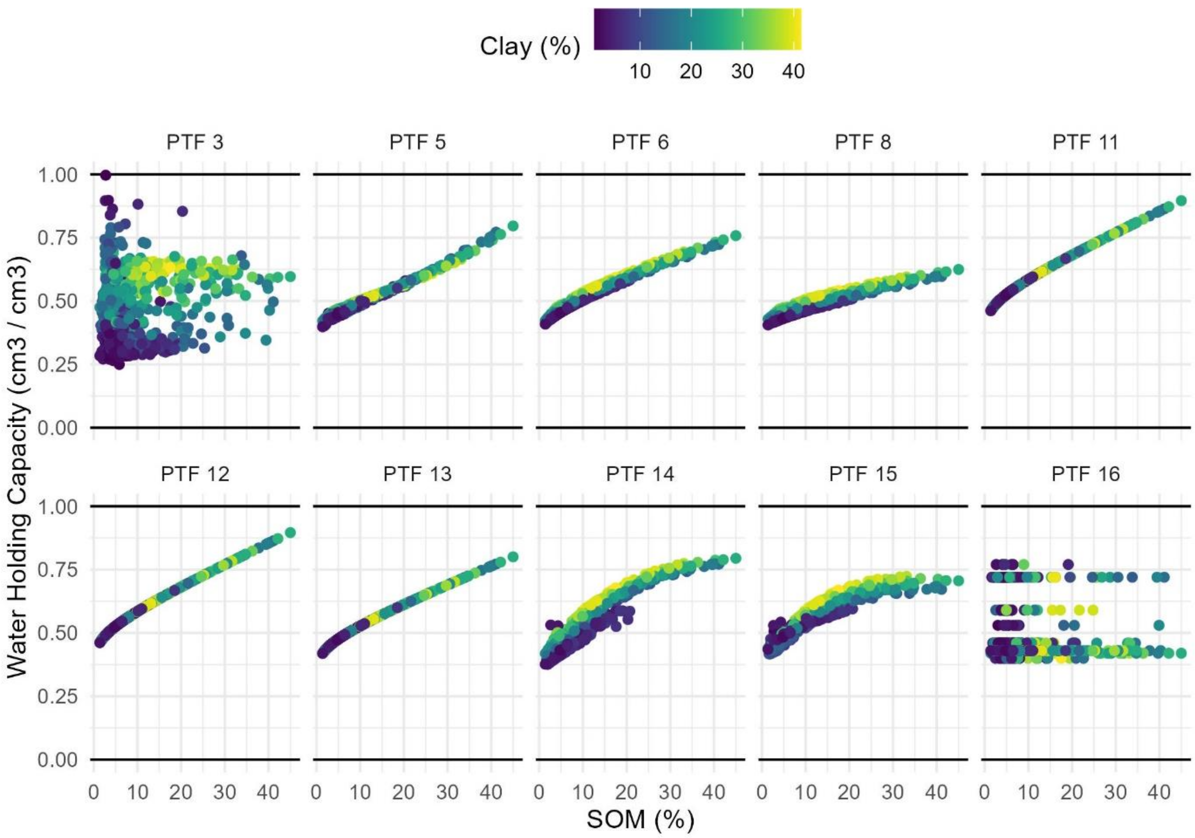


*Figure 10. Water Holding Capacity (WHC) estimated with 10 different PTFs for 1000 Dutch agricultural soils. Color depicts clay content.*

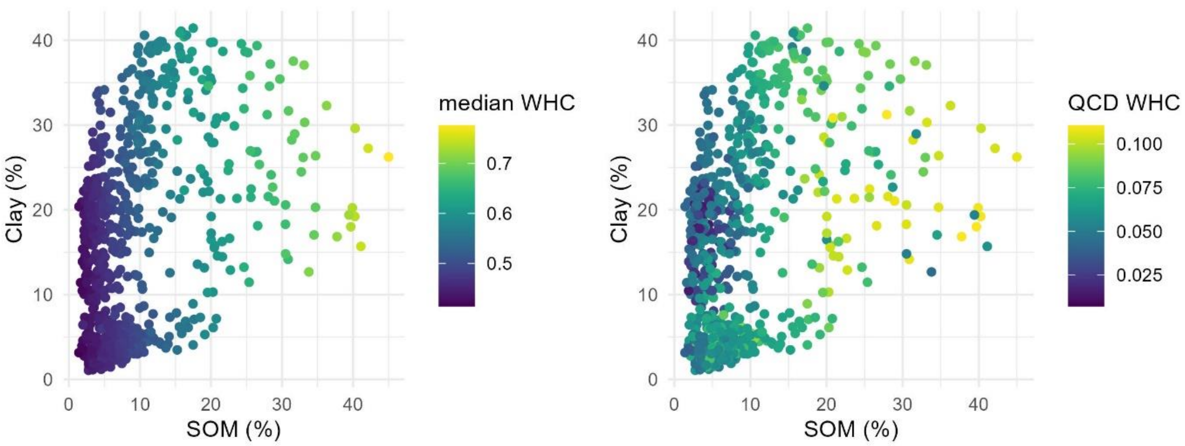


*Figure 11. Median value (left) and quartile coefficient of dispersion (QCD, right) of water holding capacity of 1000 Dutch agricultural fields, calculated with 10 PTFs. A larger QCD means a larger variation in WHC values among different PTFs.*

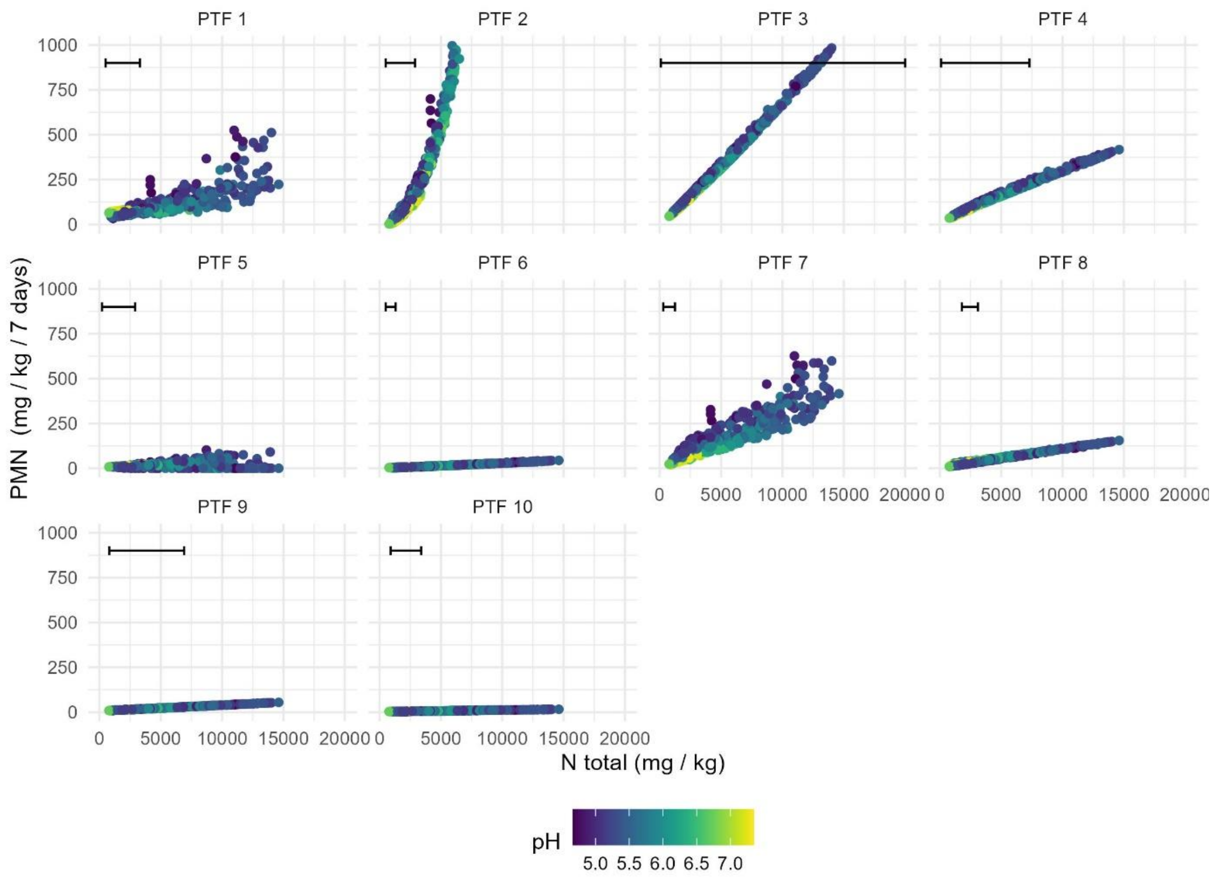


*Figure 12. Predicted potential mineralizable nitrogen (PMN) with 10 different PTFs for 1000 Dutch agricultural soils. The bars show the range of N total in the dataset on which the PTF was built. The predicted values of PTF2 for large N total values are not shown.*

*Table 4. Overview of PTFs of PAW and WHC. Type of water retention curves are BC (Brooks and Corey (1964)) and VG (van Genuchten (1980). Models are LR (linear regression), RF (random forest). paw1, paw2, paw4, paw9, paw10 are not applicable for WHC calculation.*

| ptf_id | country | continent | soilproperties | fc_kpa | wp_kpa | class | type_wrc | model | reference |
|---|---|---|---|---|---|---|---|---|---|
| paw1 | US | NA | clay \| sand \| organic C | 33 | 1500 | point | - | LR | bagdal_2022 |
| paw2 | US | NA | clay \| sand \| organic C | 33 | 1500 | point | - | LR | bagdal_2022 |
| paw3 | US | NA | clay \| sand | any | any | semi-physical | - | LR | saxton_1986 |
| paw11 | US | NA | clay \| silt \| BD | any | any | parameter | BC | LR | Campbell_1992 |
| paw12 | US | NA | clay \| sand \| BD | any | any | parameter | BC | LR | rawls_1985 |
| paw4 | CA | NA | clay \| sand \| BD \| depth | f(clay) | any | semi-physical | - | LR | oosterveld_1980 |
| paw5 | variable | EU | clay \| silt \| BD \| SOM \| topsoil | any | any | parameter | VG | LR | wosten_1999 |
| paw6 | BE | EU | clay \| sand \| BD \| organic C | any | any | parameter | VG | LR | vereecken_1989 |
| paw7 | variable | EU | clay \| sand \| silt \| BD \| organic C \| depth | any | any | parameter | VG | RF | szabo_2021 |
| paw8 | BE | EU | clay \| sand \| BD \| SOM | any | any | parameter | VG | LR | weynants_2009 |
| paw9 | BR | SA | clay \| silt \| organic C | 33\|10 | 1500 | point | - | LR | tomasella_1998 |
| paw10 | US | NA | clay \| sand \| silt \| BD \| organic C | 33\|10 | 1500 | point | - | LR | rawls_1982 |
| paw13 | variable | variable | clay \| sand \| BD | any | any | parameter | VG | LR | tian_2021 |
| paw14 | NL | EU | clay \| silt \| SOM \| topsoil \| M50 | any | any | parameter | VG | LR | wosten_1997 |
| paw15 | NL | EU | clay \| silt \| SOM \| topsoil \| M50 | any | any | parameter | VG | LR | wosten_2001 |
| paw16 | NL | EU | clay \| silt \| SOM \| M50 | any | any | class | VG | LR | wosten_2001 |

*Table 5. Overview of PTFs for PMN.*

| id | country | continent | N sample | soilproperties | type | incubation_condition | reference |
|---|---|---|---|---|---|---|---|
| 1 | variable | AF | 15 | organic C \| Fe_DTPA \| pH \| clay \| total N | regression | 30 dC, 2 weeks, anaerobic | narteh_1997 |
| 2 | CN | AS | 27 | organic C \| silt \| total N \| pH | 2-pool kinetics | 35 dC, 7 weeks, anaerobic | zou_2018 |
| 3 | NL | EU | 109146 | total N \| clay | regression | 40 dC, 7 days, anaerobic | ros_2020 |
| 4 | variable | variable | 151 | total N \| clay | regression | 40 dC, 7 days, anaerobic | ros_2020 |
| 5 | US | NA | 39 | total N \| CEC \| organic C | 1-pool kinetics | 35 dC, 30 weeks, 60 cm Hg | stanford_1972 |
| 6 | US | NA | 5 | total N \| CEC \| organic C \| pH \| clay \| silt \| RES | 2-pool kinetics | 30dC, 15 days, field capacity | cabrera_1993 |
| 7 | IN | AS | 15 | organic C \| clay | 1-pool kinetics | 32 dC, 112 days, -33kPa water potential, anaerobic | haer_2003 |
| 8 | US | NA | 6 | total N \| silt \| CEC | 1-pool kinetics | 25 dC, 28 weeks, pressure head 0.1 bar | herlihy_1979 |
| 9 | CA | NA | 33 | total N \| cult | 1-pool kinetics | 35 dC, 26 weeks, optimum moisture | campbel_1984 |
| 10 | CA | NA | 20 | total N | 1-pool kinetics | 20 dC, 55.4 weeks, -33 kPa | simard_1993 |

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