# Soil moisture regime classification of Soil Taxonomy through physically based soil water balance modelling

Antonello Bonfante[A] , Angelo. Basile[A] , Piero Manna[B] and Fabio Terribile[B]

[A]Institute for Mediterranean Agricultural and Forestry systems (ISAFOM), National Research Council (CNR), Ercolano (NA), Italy (antonello.bonfante@gmail.com)
[B] Department of Soil, Plant, Environmental and Animal Production Sciences, University of Naples Federico II, via Università 100, 80055, Portici (Na), Italy

**Abstract**
Soil Taxonomy classification differs from other systems as it includes estimation of the soil moisture regime (SMR). Currently, its estimation is obtained through simple calculation schemes, such as the Newhall and Billaux models (standard approaches) or the EPIC model.

The aim of this work was to use a physically based model SWAP for evaluating Soil Taxonomy – SMR in eight Italian sites with different pedoclimatic conditions. The SMRs obtained were compared to those applying Newhall and Billaux models, as well as the ICOMMOTR proposals.

In general, the standard approaches showed unrealistic results. They overestimated the dry conditions in the soil moisture control section (SMCS) during the year but allows the separation of different pedoclimatic settings. In contrast, the physically-based approach showed realistic results but it was not able to differentiate various pedoclimatic settings (almost all sites as Udic). Simulation modelling was then used to evaluate the sensitivity of the model output, namely SMR, by varying model inputs such as the dry limits values (-1500 kPa) for SMCS. Finally, a tentative proposal was designed that enlarged the SMR classification to include some information on the dynamic behavior of the soil-climate system so that the system may better perform in current environmental challenges.

**Key Words**
Soil moisture regimes, Newhall, SWAP, Soil Taxonomy.

## Introduction
Climate is one of the most important soil forming factors affecting soil processes, soil properties and in turn the use of soils. Soil Taxonomy (Soil Survey Staff, 2006 uses climate information to classify soils by means of the soil moisture regime (SMR). SMR is typically calculated through the use of well known models such as Newhall (Newhall 1972; Van Wambeke 2000), Billaux (Billaux 1978), and more recently EPIC (Costantini *et al.* 2002). These models estimate the SMR through simple calculation schemes, based on the precipitation-evapotranspiration balance that frequently produce incorrect soil water flow predictions because are not based on physical laws. The arising question is whether they properly classify SMR and define soil moisture control section (SMCS). This work addressed these problems by evaluating, through the use of a calibrated and validated physically based water balance simulation models (SWAP, van Dam *et al.* 1997), the appropriateness of Soil Taxonomy criteria and also the International Committee on Soil Moisture and Temperature Regimes (ICOMMOTR) proposals (ICOMMOTR 1991) on selected Italian soils.

## Methods
*Criteria of SMR classification in Soil Taxonomy and ICOMMOTR*
SMR classification was done according to Soil Taxonomy and the ICOMMOTR proposal.

*Model applied to classify SMR*
The Newhall and Billaux models (standard approach) which calculate itself the potential evapotranspiration through the Thornthwaite formula (Thornthwaite 1948).
The physically based model SWAP.

*SMR Elaborator*
In order to classify the SMR with the output of the physically-based model SWAP, a routine in Visual Basic for Excel called “SMR Elaborator” was developed, and is available upon request.

 
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*Sites*
The eight soils studied were distributed in northern (six) and southern (two) Italy. They included very diverse Inceptisols, Alfisols, and a Vertisol. The SWAP model was calibrated and validated in the eight soils. The field and laboratory measurements and procedures to calibrate and validate the model were done as previously described (Bonfante *et al.* 2009; ERSAF 2007; Basile and Terribile 2008). The sites have been calibrated and validated in different years.

The daily climatic data applied for each site and year are: (i) air temperature (min and max), (ii) rain, and (iii) reference evapotranspiration estimated through the Penman-Monteith equation (Monteith 1965).

**Results**
The classification of SMR was conducted by two different methods: a standard approach based on two widely applied classification models (Newhall and Billaux), and a physically-based approach based on the hydrological model SWAP, to determine SMCS and the soil water potential over time (Figure 1).
In order to determine the boundaries of the SMCS, according to the Soil Taxonomy definition, the physically-based SWAP model was applied to the eight sites simulating the deepening of the wetting front. The results (Figure 2) shows that: (i) the SMCSs thickness estimated by SWAP were close to those reported in Soil Taxonomy (Keys to Soil Taxonomy, pp.26, Soil Survey Staff 2006) for different soil texture classes but quite different from those obtained using the Newhall and Billaux models; (ii) the control section applied by the Newhall and Billaux models were in many cases unrealistic (e.g. Mantova, Ghisalba, Eboli); and (iii) in some cases the Newhall and Billaux models largely overestimated the lower boundary of the SMCS with an unrealistic estimation (e.g. Ghisalba site -118 cm).

Table 1 shows the SMR obtained by several approaches: (i) applying the SWAP model using the crop and lower boundary condition (presence/absence of water table) as measured in the running year, (ii) applying the SWAP model without using the crop and water table in order to emphasize the role of soil, (iii) applying the Newhall model and (iv) the Billaux model. Apparently, the three models give the same result for five sites (Udic moisture regime). However, further detailed analysis showed that the Newhall and Billaux approaches produced dry conditions in the SMCS (in some or in all parts) for several days during the year (e.g. the Mantova site in 2003 has 80 dry days using the Newhall model and 127 days using the Billaux model) while using SWAP the SMCS was always moist (in some or in all parts).
To further investigate the comparison between the physically-based and standard approaches, SMR classification with the Newhall and Billaux models using the same Et0 applied in SWAP was performed (Table 1, columns with §). The standard approaches showed unrealistic results with very high dryness values.

The classification using ICOMMOTR methodology fit that obtained with SWAP among those applied using Soil Taxonomy. The results suggested that the ICOMMOTR classification was similar to the classification after using the physically based approach, despite its simpler structure. Nevertheless, this approach required water potential measurements or estimates from calibrated hydrological models.

Based on the results obtained, we have attempted to produce some possible Soil Taxonomy methodology improvements, at least for the range of the investigated soils, with a sensitivity analysis of the dry limit values (-1500 kPa) on the SMR classification. The results of this sensitivity analysis showed that the Udic SMR comprised most of the dry limit range, producing a clear overestimation in respect to the other classes, almost irrespectively of the soil and climate conditions. In detail, in 50% of cases the transition between the Udic and Ustic regimes classification occurred below -40 kPa, and the transition between moisture regime classes occurred at -13 and -200 kPa. Indeed, these values physically correspond to wet soil conditions.

A new proposal was formulated for further implementation of the SMR classification to provide additional information on the soil-climate behavior using a physically based hydrological model. In detail, the classification proposed (Soil Driven Moisture Regimes Classification – SDMRC) was obtained through the use of two functional indices obtained from the simulation outputs with SWAP with bare soil in one year of analysis (normal year). The first index ($I_{dr}$) considered the exchanges of water at the bottom boundary of the soil system, and it consisted of the ratio between the annual drainage (estimated by the model) and the annual water inputs applied to the soil system (rain). The second index ($I_{ev}$) considered the exchange of water at the soil upper boundary, namely between the soil system and the atmosphere, and it was defined as the ratio between actual annual soil evaporation (estimated by the model) and potential annual soil evaporation. Both indices were expressed as a percentage and their combination enabled the estimation of the SMR in accordance with Soil Taxonomy criteria.

**Table 1. Classification of SMR with Soil Taxonomy and ICOMMOTR methodologies.**

| Sites | Year | Soil Taxonomy Moisture regime | | | | | | ICOMMOTR Moisture regime |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Penman-Monteith $ET_0$ | | |
| | | SWAP† | SWAP†† | Newhall | Billaux | Newhall§ | Billaux§ | |
| Mantova | 2002 | Udic | Udic | Udic | Udic | Ustic | Aridic | Udic Ustic |
| | 2003 | Udic | Udic | Xeric | Xeric | Xeric | Aridic | Udic Ustic |
| | 2004 | Udic | Udic | Udic | Udic | Ustic | Xeric | Udic Ustic |
| Caviaga | 2002 | Udic | Udic | Udic | Udic | Udic | Xeric | Perudic |
| | 2003 | Udic | Udic | n.a. | Xeric | n.a. | Aridic | Typic Udic |
| Carpaneta | 2005 | Udic | Udic | Udic | Udic | n.a. | Xeric | Typic Udic |
| Ghisalba | 2005 | Udic | Udic | Udic | Udic | Udic | Udic | Perudic |
| Landriano | 2005 | Udic | Udic | Udic | Udic | n.a. | Xeric | Typic Udic |
| Luignano | 2005 | Udic | Aquic | Udic | Udic | n.a. | Udic | Perudic |
| Scafati | 2005 | Udic | Udic | Xeric | Udic | n.a. | Udic | Typic Udic |
| Eboli | 2004 | Udic | Udic | Ustic | Udic | Xeric | Xeric | Typic Udic |
| | 2005 | Udic | Udic | Xeric | Udic | Xeric | Xeric | Perudic |

§ Models were performed applying the Penman-Monteith equation to calculate reference evapotranspiration ($Et_0$) as in the SWAP model.
† Real management condition
††Without water table and plant growth
n.a.: Not available

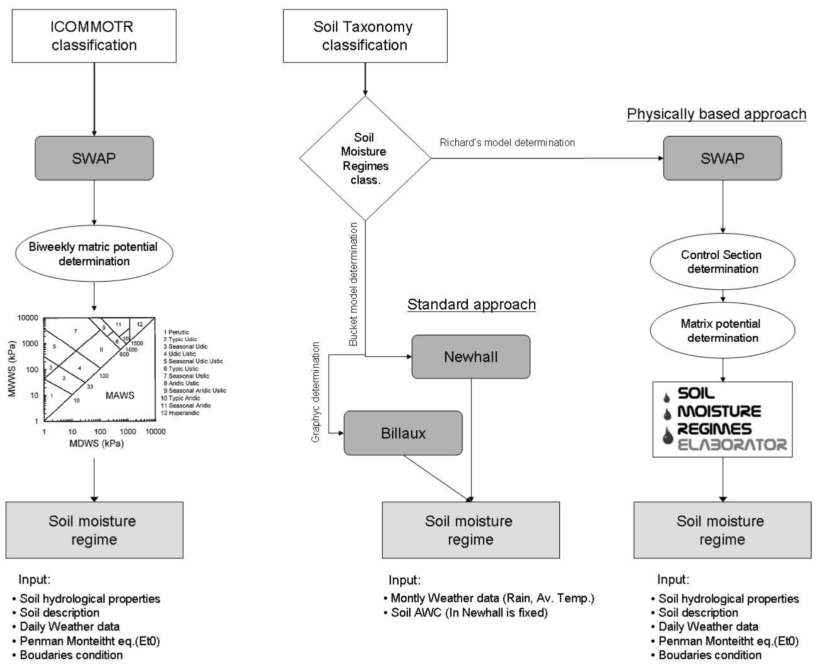


**Figure 1. Schematic diagram of the procedures adopted for SMR classification.**

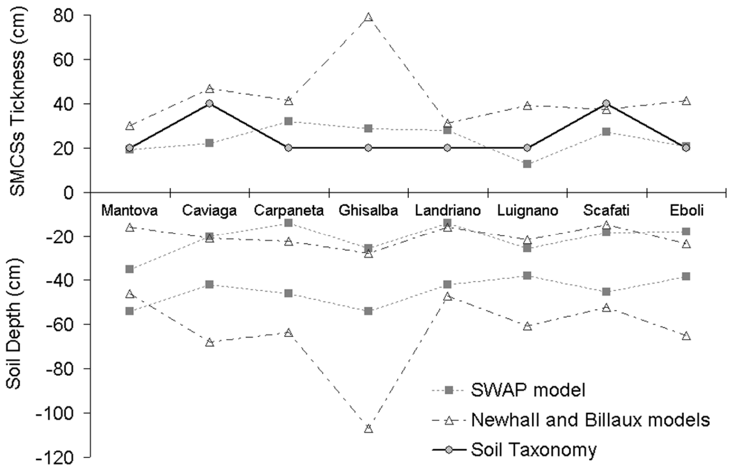


**Figure 2. Upper: SMCS thickness of the eight soil samples according to SWAP (square), Newhall and Billaux (triangle) models, and Soil Taxonomy (circle). Lower: upper and lower boundaries of the SMCS determined using the SWAP model (square) and the Newhall and Billaux models (triangle).**

## Conclusion

The use of a physically-based approach showed that indeed some problems exist in the application of the SMR classification method proposed by Soil Taxonomy, at least for the studied sites. In our case studies, the use of standard approaches to classify SMR according to the Soil Taxonomy scheme showed unrealistic results but enabled the separation of different pedoclimatic settings. In contrast, the application of a calibrated and validated (in the eight study sites) physically-based approach, as expected, showed realistic results but was not able to distinguish different pedoclimatic settings. These findings suggest that if physical laws are applied, the strict scheme and criteria of SMR classification in Soil Taxomomy do not distinguish the different pedoclimatic settings ranging from Southern to Northern Italy. A tentative proposal was also provided for a SMR classification aiming to enlarge this procedure in order to meet new environmental issues, which often require the dynamic hydrological behavior of the soil-climate system to be addressed.

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