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The influence of physical soil properties on the water supply of irrigated orchards-some examples from Val Venosta (South Tyrol/Northern Italy)

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Abstract

In irrigated agriculture, irrigation water volume and duration of irrigation can be optimized utilizing soil water dynamics data. Val Venosta in South Tyrol (Northern Italy) is a region where irrigation represents a central factor of production in the Tyrolese fruit-growing areas. Intensive orchard production is practised within an area of about 18.000 ha. Although fruit cultivation experts believe that intensive fruit cultivation should be based on regular irrigation of the fruit trees to guarantee optimum results in both fruit quantity and quality; however, fruit growers in the region follow very subjective criteria in regard to irrigation. At many locations much more water is used than the fruit trees actually need. Therefore irrigation in this region is a very cost-intensive factor of production and is criticized by the public for both economic and ecological reasons. To optimize the irrigation practice in this region it is essential to provide an objective basis for the irrigation process. A system of "precision irrigation" proposed, which is therefore based on objective and quantitative criteria focusing primarily on soil properties and hydrologic balance. This contribution will provide an overview of the current situation of irrigation and present results from soil-physical and soil-hydrological studies performed in this region since 2003.

Key words

Soil water dynamic, Precision irrigation, Soil physics, Soil hydrology, Soil distribution

Introduction

About 20% of the cultivated area of the earth must be irrigated because of limited precipitation (Mujambdar, 2004). Irrigation therefore represents an essential and indispensable factor of production whose necessity will continue to be important in future. Climatic factors partially determine hydrological balance in soils. Soil physical properties must also be considered to evaluate plant available water. Because of the small-scaled spatial variability of soil properties, soil water conditions and soil water fluxes are subject to spatial and temporal variations. Variability of soil water and hydrologic properties is present in the horizontal and vertical dimensions. In many regions of the world, where a lucrative harvest can only be guaranteed by irrigating, soil variability is a major challenge and requires consideration of a system of precision irrigation.

This contribution will provide an overview of the current situation of irrigation and present results from soil-physical and soil-hydrological studies conducted in the Val Venosta, Italy region since 2003. Because of the climatic conditions irrigation has always been a necessary factor of production in this region. More than 85% of the orchards in Val Venosta are equipped with a sprinkler overhead irrigation system. Current grower irrigation practices are usually based on subjective criteria and the overhead sprinkler system causes an unfavourable distribution of the irrigation water on the soil surface (Fig. 1). The density of the artificial precipitation may range between 2 mm hr^{-1} and 6 mm hr^{-1} under a constant operating pressure (Thalheimer and Paoli, 2004).

The current haphazard system of this irrigation wastes great quantities of fresh water and energy. A conscious reduction of irrigation intensity would be beneficial in many soils within the region with regard to the apple production (Thalheimer *et al*., 1999). Furthermore, excessive irrigation may contaminate groundwater with nutrients. Some soils within orchards already have very high groundwater in relation to the soil surface and probably should not be irrigated at all (Thalheimer, 2005; Grashey-Jansen, 2008a; Grashey-Jansen and Eben, 2009). A reduction in irrigation is supported by a survey of soils in the region with high groundwater levels that would naturally supply water to the trees if given the opportunity to do so groundwater influenced locations (Grashey-Jansen, 2007a,b, 2008b). On these soils irrigation is very unfavourable-nevertheless they are irrigated and the physical soil properties and conditions of these areas are ignored.

The current agricultural consumption of water in South Tyrol of 150 Mio m^3 per annum is twice as high as the industrial water consumption in the region. The guidelines of the European water framework directive places legal constraints on the use of irrigation water, making it necessary to optimize irrigation to meet production requirements. Irrigation must be oriented towards the actual water need of the plants and the physical and hydraulic properties of the soils. A system of "precision irrigation" is increasingly considered.

Materials and Methods

Study area: South Tyrol in Northern Italy is the largest coherent apple growing area in Europe (18.000 ha and an annual production up to 900.000 t). The mix of Mediterranean and middle European climatic conditions is ideal for intensive crop cultivation (Grashey-Jansen and Schröder, 2009). In Val Venosta (Fig. 2) profitable orcharding is possible up to 1.100 m above sea level. The annual precipitation averages between 450 to 550 mm.

The distribution of soil types within the Val Venosta region is very heterogeneous. In general, hillsides are dominated by *Leptosols* and *Cambisols*. Most of the soils on the valley floor are *gleyic Cambisols*, partially *calcaric Fluvisols* or *Gleysols* (Grashey-Jansen and Schröder, 2009). Many orchards of Val Venosta are very shallow to groundwater and reductive pedogenetic processes can easily be detected. Evidence of these processes is the presence of *Gleyosols* and other soil types with *gleyic* properties.

Experimental design: The database used for soil physical and statistical analysis was gained by specially constructed measurement protocols to determine the systematic interdependencies of water-balances of the regional soils under the influence of irrigation. Use of special programmed data loggers allowed the recording of relevant parameters at hourly intervals (Grashey-Jansen, 2008a). These protocols were established in 18 representative locations (Fig. 2) chosen to quantify pertinent soil properties and soil hydrology.

A primary hydrologic property measured at each location was soil water tension at soil depths of 20, 40, 60 and 80 cm. These depths were chosen because of the root systems and root depths of apple trees and the potential influence of groundwater on the soil water tension at some locations. Soil water tension is an important time series measurement because it provides data regarding the portion of water available to the trees at a moment in time. These measurments, conducted at different depths also aided in calculating the vertical water flux in the soils through calculating hydraulic potential-gradients.

Additional measurements at each location included rainfall, length of time of irrigation, relative humidity, soil temperature in 15 and 30 cm depth, air temperature inside and outside of the orchards, the water level of nearby rivers/streams and groundwater. These

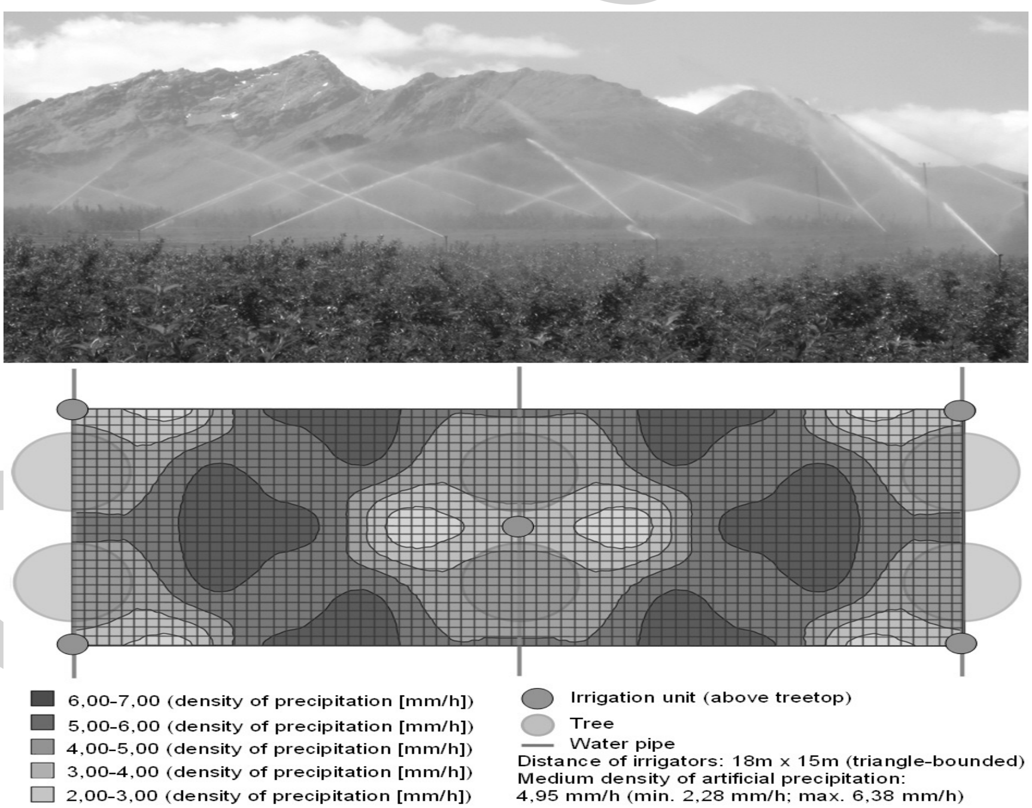

Fig. 1: Heterogeneous distribution of the irrigated water in the orchard (irrigation: triangle units). (modified according to Grashey-Jansen and Timpf , 2010 and Thalheimer and Paoli, 2004)

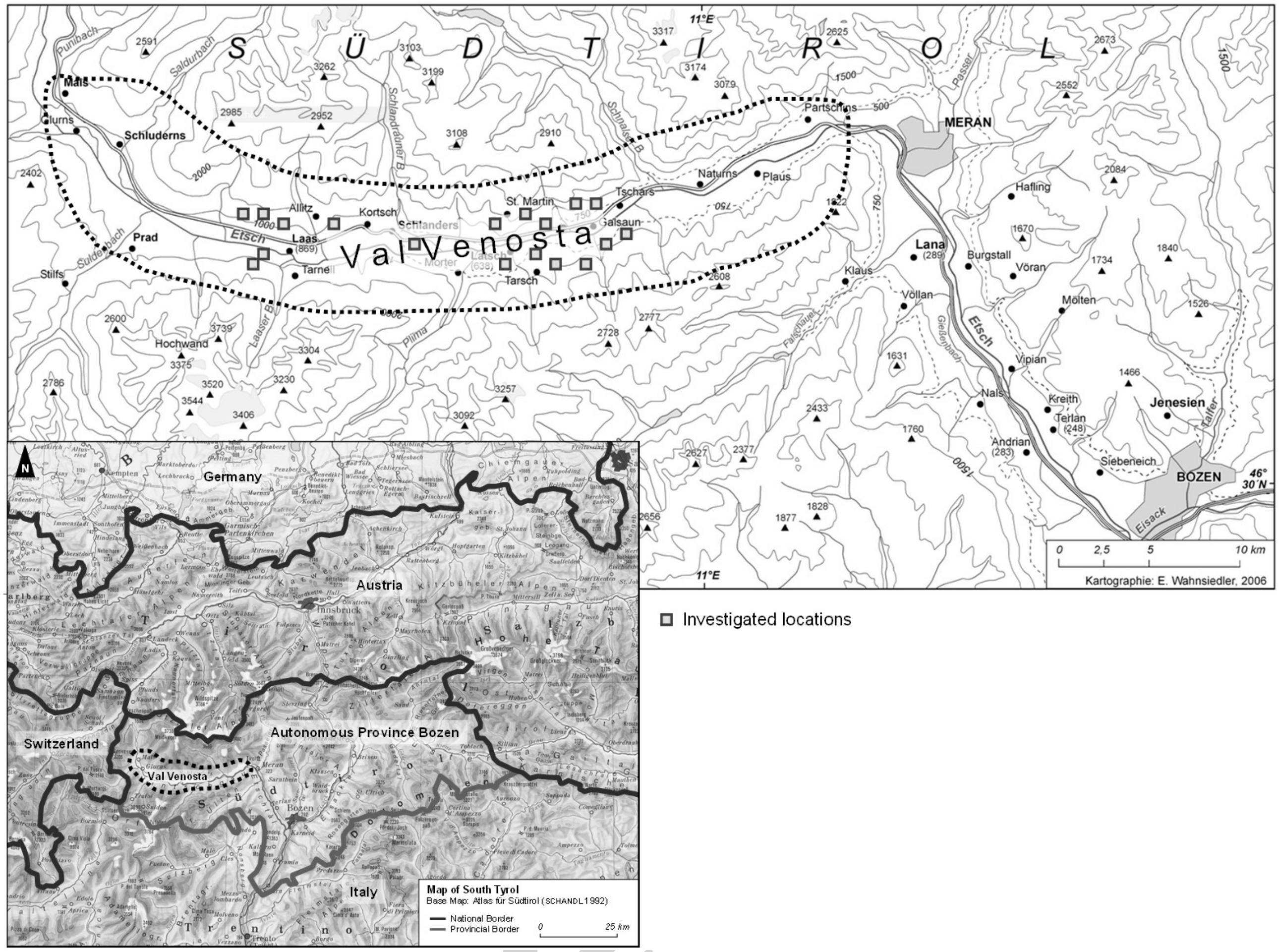

Fig. 2: Study area Val Venosta in South Tyrol, Italy, showing experiment locations

data bases were supplemented by infiltration-rate experiments and physical soil analysis conducted in the field and laboratory. Particle size analysis was also conducted.

Statistical analysis: The experimental data bases were used to quantify relationships between factors using a variety of relevant statistical methods. Numerical low-pass-filters were used to detect and describe longer termed variations and marked phases of anomalies in the history of tensiometrical time series. Numerical high-pass-filters were also used that allowed the optimized analysis of high-frequency-variabilities. Bivariate and partical correlation analysis were used to quantify relationships between soil water tension and other parameters. Inertia-influenced reaction speed and repetition patterns calculations of partial auto correlation functions (ACF) were executed to identify location and depth specific properties. Relevant time-lags were calculated using cross-correlations (CCF) for all correlation pairs to quantify within soil-hydrological processes natural temporal delays as well as the relationships and reaction speeds connected with them. Principal component analysis (PCA) helped to extract the most relevant variability tendencies of soil water tension measurements and to condense the time series data. Calculation of nonlinear multiple regression functions (MRC) made it possible to select parameters of influence which contribute significantly to explain the variations of soil water tensions.

Results and Discussion

Soil analysis: Fig. 3 shows the structure of soil at three different locations which were used as examples in presenting the results. The genesis of the soil at location ST1 (*fluvi-eutric Cambisol*) and ST8 (*fluvi-calcaric Regosol*) is influenced by their landscape position on the valley floor. The soil at location ST4 (*cambric Regosol*) was formed from landslide materials. Location ST8 is characterized by a high subsoil water table. The profile of this soil consists of a very sandy soil matrix (Fig. 4). From about 40 cm depth, the soil-horizon A(*g*) (with groundwater influenced and gleyic properties) was nearly 100% sand. The groundwater is close enough to the surface at this location and rises near or to the surface through capillary rise. The tensiometric contact at the 80 cm soil depth is greatly influenced by groundwater depth. Capillary rise is a temporal influence on soil water content available for uptake by the main active water uptake root system of the apple trees.

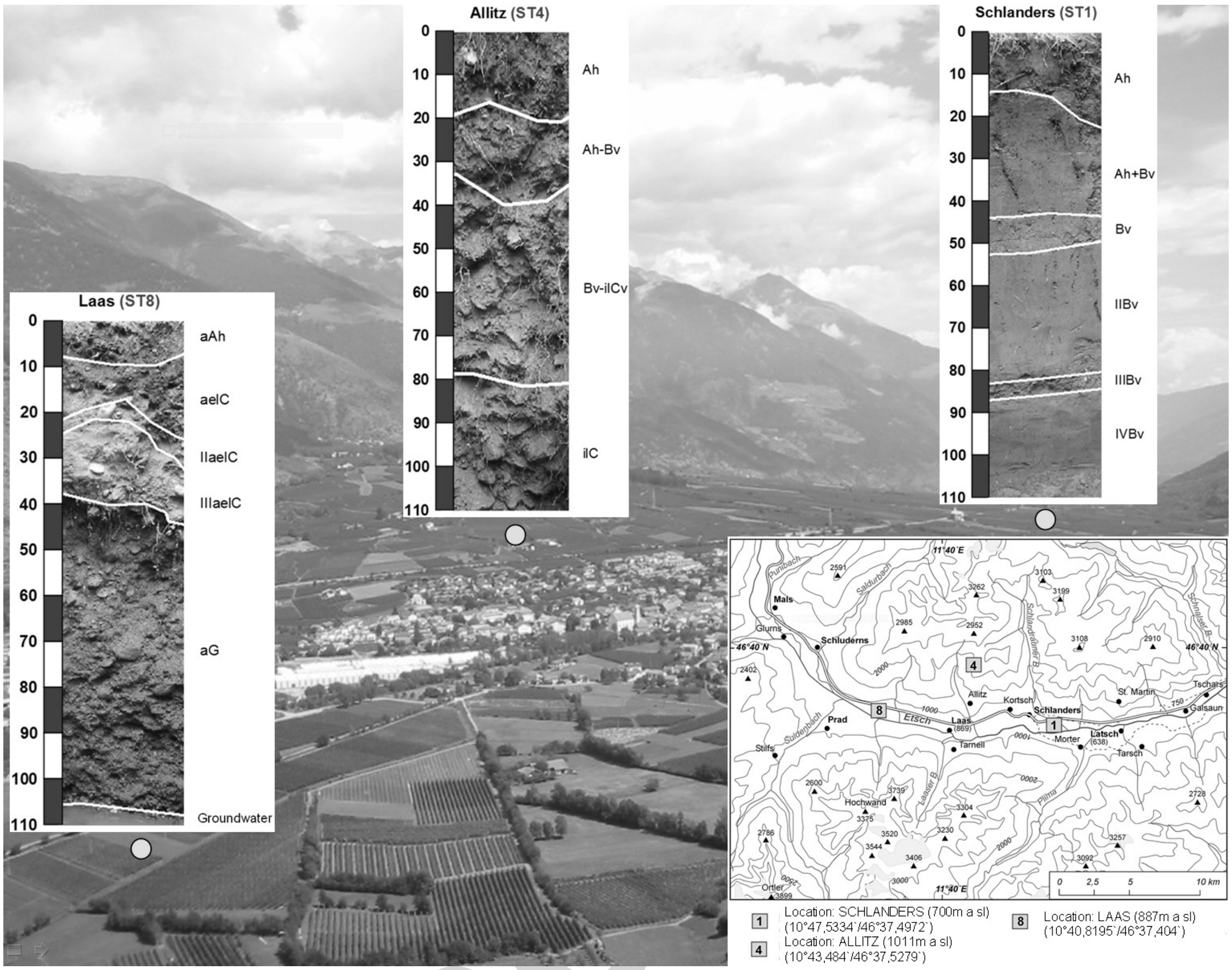

Fig. 3: Three exemplary locations in the irrigated orchards of Val Venosta and their soil profiles

Tensiometric and statistical analysis: Soil water tension was dependent on soil depth (Fig. 5). In soil < 40cm in depth, atmospheric influences had a major impact on soil water tension (Grashey-Jansen, 2008a). At most sites the matric potential of the upper soil depths changed more quickly with irrigation than lower depths. At locations with a proximity to groundwater, the groundwater level strongly influenced the soil water tension at the 60 and 80 cm depths. The majority of the orchards were located in these valley floor landscape positions. Therefore, most locations were influenced by these floodplain dynamics and high ground water table.

In current orchard management, measurement of the volumetric soil water content is often used to determine whether or not to irrigate. Volumetric soil water content is also used to the scheduled irrigation duration time and the amount of water to apply; however, use of this parameter alone is not suitable for most of these decisions because plant available water is determined by matric potential. Fig. 6 shows the relationship of the matric potentials and the volumetric soil water contents for the corresponding soil textural classes at the 40 cm depth at locations ST1, ST4 and ST8. The relationships were calculated for the whole pF-range by using special self-developed pedotransfer functions for these soil textural characters (Grashey-Jansen and Timpf, 2010). The volumetric water content in the root zone of location ST1 amounts to about 27 % at pF 2,8 and to about 13% at pF 4,2 (Fig. 6). This indicates the comparatively higher clay content in this horizon. In contrast, the sandy substrate at the same depth at location ST8 had much of its water held in large pores that drained at low suctions. In principle the water content in the root zone of the shown locations differed notedly within the relevant pF-range. Due to the fact that the same volumetric content corresponds in dependence of the soil texture with different matric potentials, volumetric water content was not a good enough predictor alone for irrigation management.

The hydraulic gradients were calculated on the basis of tensiometric time series at different depths to obtain information regarding vertical water flux. A predominance of a downward water movement between 20 and 40 cm under surface could be observed whereas between 40 and 60 cm these relations were much less distinct (Fig. 7). Between 40 and 60 cm sometimes upward soil water fluxes occured. The upward capillary water movement in the depth zone between 60 and 80 cm (only measured in 2005) was

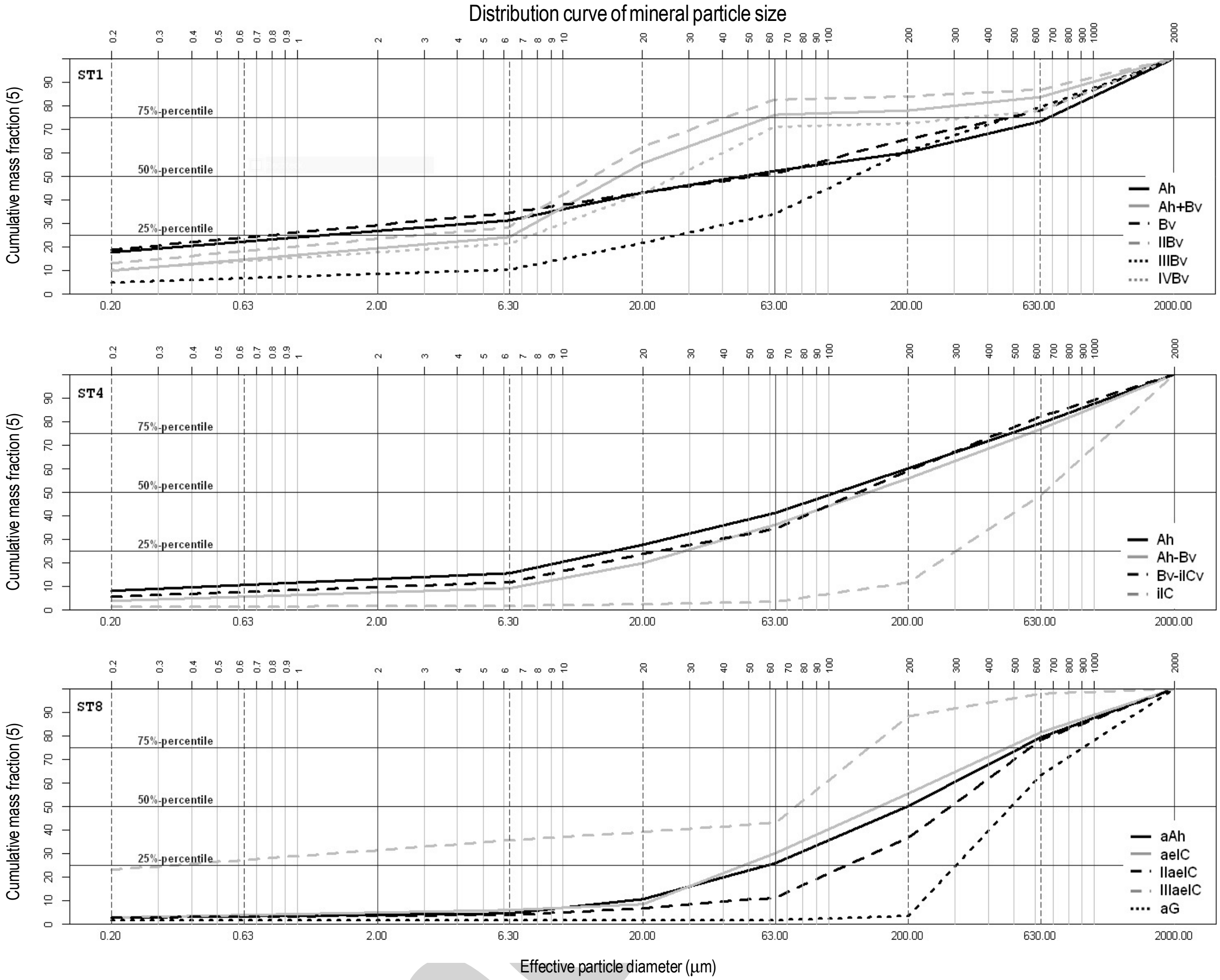

Fig. 4: Distribution curve of mineral particle sizes in the soil horizons at the three example locations (denotation of the soil horizons according to German guidelines of soil science).

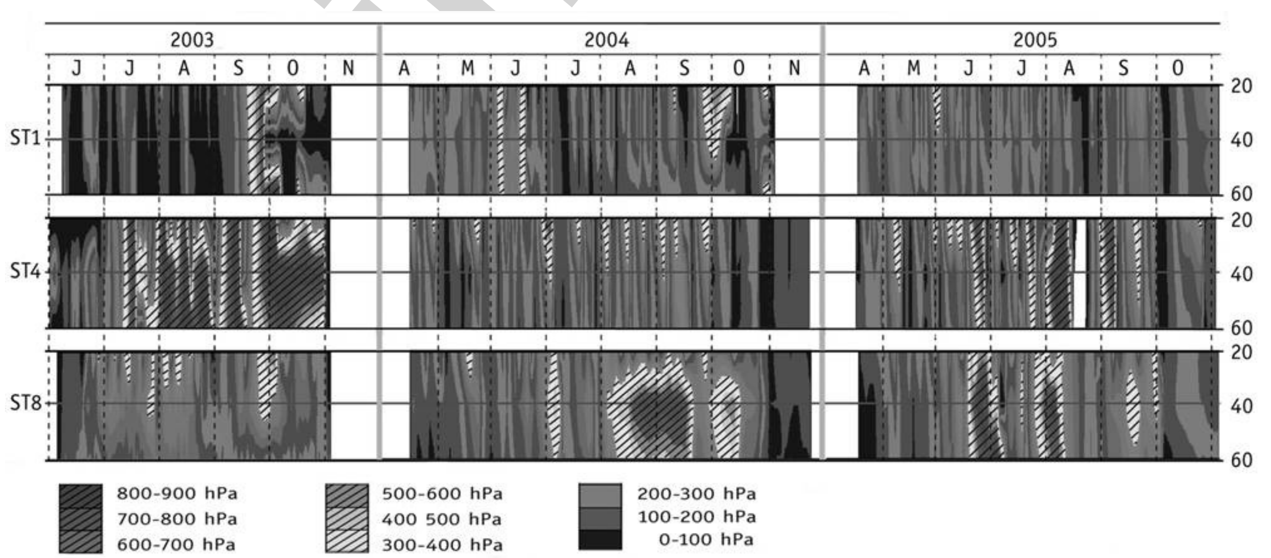

Fig. 5: Isotensions of the soil matrix potentials at the three example locations.

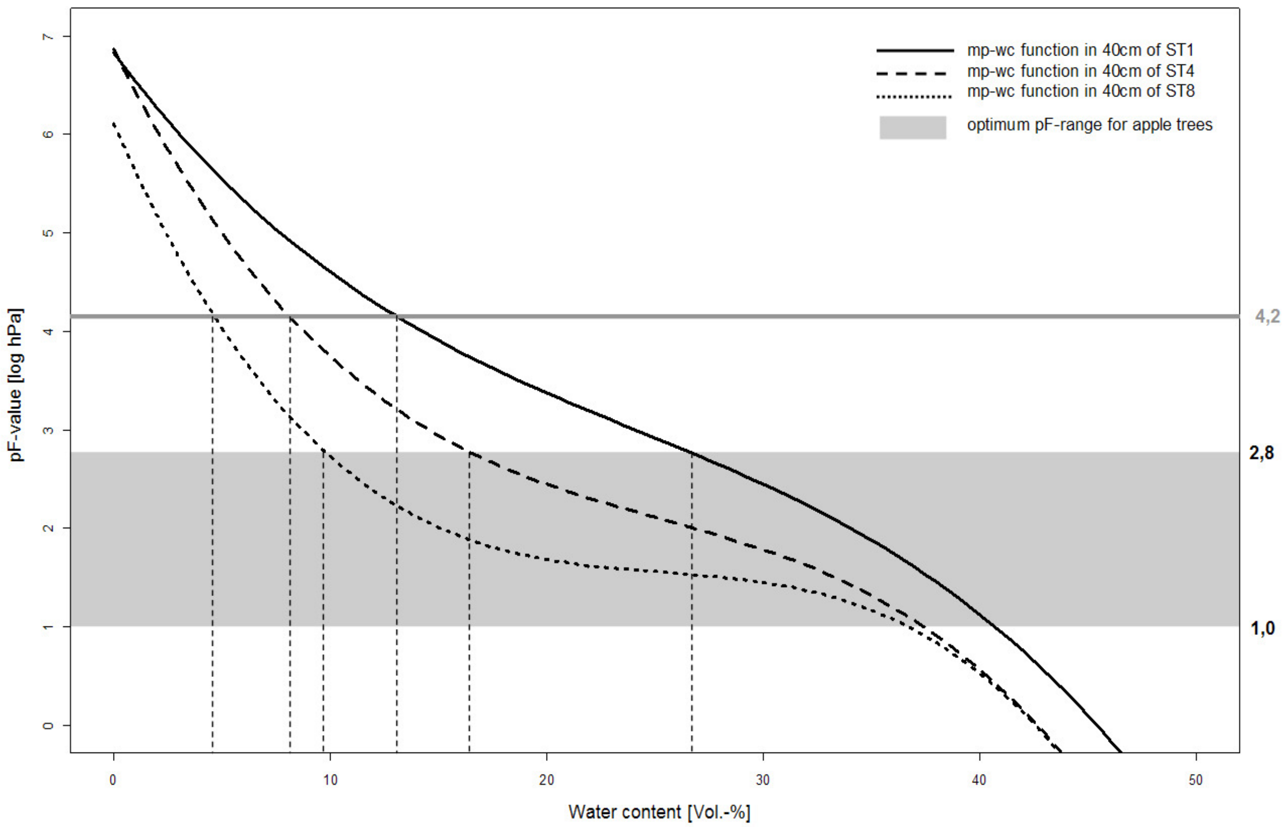

Fig. 6: Matric potential (mp) - water content (wc) function in the root zones (40cm soil depth) of the discussed locations.

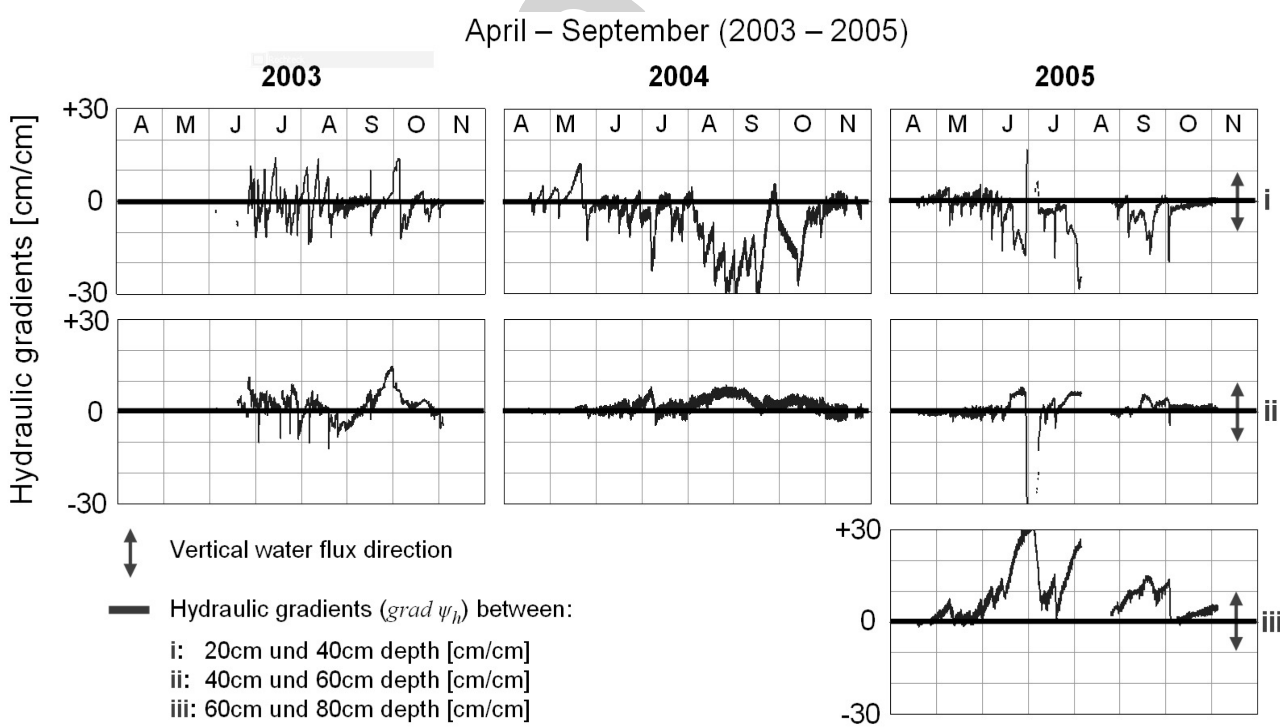

Fig. 7: Progress of hydraulic gradients *graph* between different depths at the observed location ST8 from April to November 2003, 2004 and 2005).

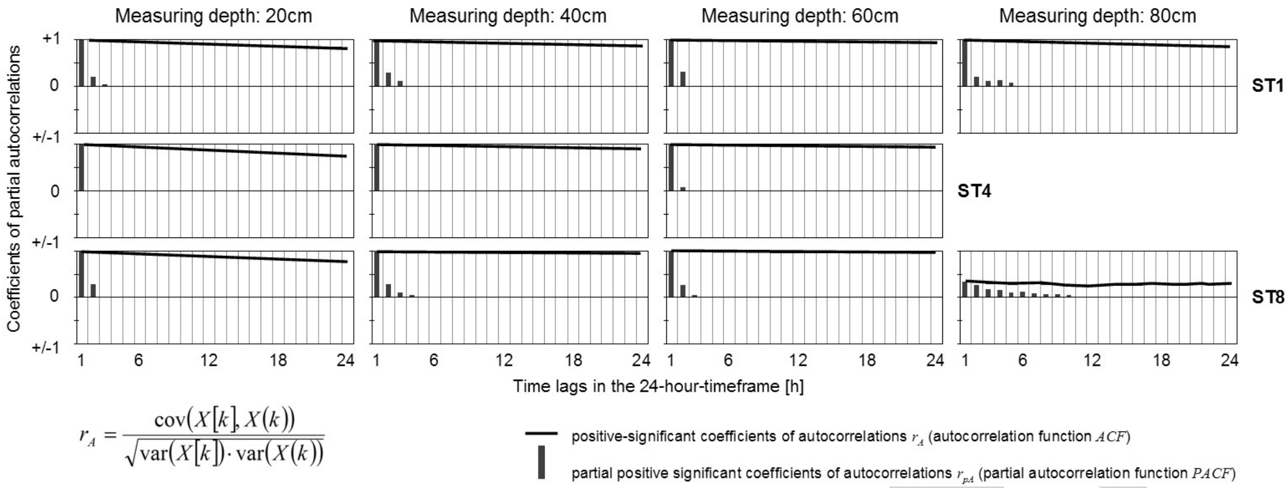

Fig. 8: Positive significant coefficients of partial autocorrelation of the tensiometric data sets in different depths in the 24-hour timeframe (significance level between $\alpha < 0.001$ und $\alpha \leq 0.05$)

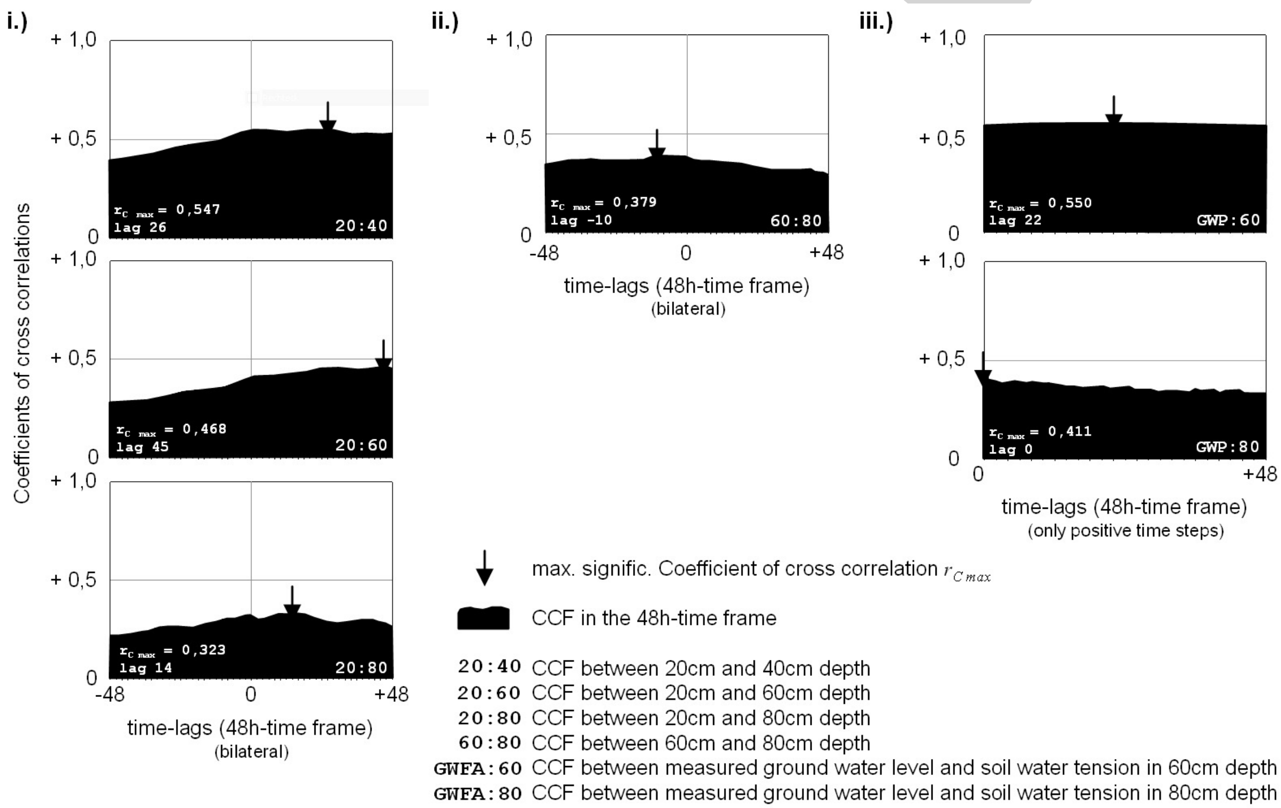

Fig. 9: Significant coefficients of cross-correlations in the 48 hr timeframe (significance level $\alpha = 0.01$) - (i) Time lags of tensiometric data sets (between 20, 40, 60 and 80 cm at location ST8), (ii) Time lags of tensiometric data sets (between 60 and 80 cm at location ST8), (iii) Time lags of tensiometric data sets (60 and 80 cm) and data sets of groundwater level (at location ST8)

due to the high groundwater table at the site. The results of the ACFs mapped in Fig. 8 shows a progressive inertia of the matric potentials with increasing soil depth. The fact that the interval of persistence was extended up to 10 hr in 80 cm under the soil surface level implie that the soil water tension changes lost their dynamics because this parameter becomes increasingly uncoupled from the climatic influences with increasing soil depth.

The CCFs (Fig. 9) also showed an increased time lag of change with soil depth. Slower dynamics in the matric potentials down to 60cm depth (26 hr from 20 to 40 cm and 45 hr from 20 to 60 cm) were detected. The high position of groundwater explained that the shortest time lags were calculated for the signal between 20 cm and 80 cm after only 14 hr. The results of the CCF for the time series of the soil water tensions between 60 and 80 cm in Fig. 9

showed a negative time lag of 10 hr. This must be explained soil-physically by the temporal advance of the reactions of the matric potentials in 80 cm depth in contrast to those in 60 cm depth. By including the time series of the groundwater levels into the CCF-calculations the signal-change in the groundwater level was registered only after 22 hr by the soil water tensions in the depth of 60 cm and 0 hr in 80 cm soil depth. That implies that the signal time lag took less than 1 hr, so it was not measurable with the temporal resolution used in this study.

The hydrological communication happens despite a vertical distance (on average 30-40 cm) between the groundwater level and the upper soil layers because of capillary rising processes. The effect of capillary rising in the soil depth of 60 cm was largely absent because the sandy and porous soil texture (Fig. 4) did not allow higher rates of capillary rising (maximum rising rates of about 3-5 mm day^{-1}) and so the level in 60 cm depth was not influenced by this process.

The results of the PCA and the MRC are not presented in this paper but both verify the depth-specific influence of groundwater in the main root area of apple trees (Grashey-Jansen, 2008a,b,c). This indicates that the water supply of orchards with a high subsoil water level may be primarily achieved by capillary rising so that an intensive irrigation is needless and counterproductive.

Recently, attention has been given to improve cultural practices including subsurface irrigation and partial root zone drying irrigation (Banedjschafie *et al*., 2008; Saeed *et al*., 2008; Greenwood *et al*., 2010). The composition and physical properties of the soil profiles play an important role in these irrigation methods even if there are small scale soil differences at the irrigated locations.

Precision irrigation must be based on objective criteria such as water distribution in the soil and pedological conditions. To optimize irrigation practice in an objective way it is important to give close attention to the pedological conditions. If these conditions are known it would be much easier to calculate the effectiveness of atmospheric sources of influence against the costs of supplemental irrigation. Novel irrigation equipment requires a fine control of the water distribution in the soil. One idea is to control the irrigation by means of pedospecific calibrated moisture sensors near the plants' roots and their integration in a sensor network producing a dynamic real-time irrigation plan (Grashey-Jansen and Timpf, 2010). Such an irrigation plan adapts to measured soil water dynamics, differentiating between different soil strata and soil depths. But precision irrigation must not only be realized by the usage of high tech methods. Also local pedological knowledge in combination with the longstanding experience of the regional agriculture may achieve good results.

In this paper the problem of the actual irrigation has been presented. The natural characteristics of soils should be regarded as an important factor for the soil water dynamics. This contribution also indicates that the benefit from irrigation primarily depends on the pedological properties of the soils. Irrigation efficiency is very variable, depending on location and soil depth relative to crop rooting depth. The influence of pedological characteristics with its spatial variability controls the infiltration characteristics of the soil and the relationship between the volumetric water content and the matric potentials. This study also documents the influence of capillary rise in the soils. The presented results attest that the main root system of the apple trees at locations with high groundwater levels can be enough supplied with water from a deeper soil layer or aquifer through capillary rise.

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