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# Real-time detection of root zone-$CO_2$ and its potential for irrigation scheduling

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The suitability of root zone-$CO_2$ measurements (WR-$CO_2$) for irrigation scheduling was investigated and evaluated. The basic assumption was that plants reduce root respiration as a reaction to water deficit. A study with apple trees proved that measured WR-$CO_2$ originates in large parts (56–72 %) from plant specific $CO_2$ production (mainly root respiration). Furthermore, WR-$CO_2$ reacts to irrigation as well as correlates with soil water content. Since WR-$CO_2$ variations were also reflected in changes of plant water status, basic potential of WR-$CO_2$ for irrigation demand assessment of the investigated apple trees is apparent. The transferability to other crops will be investigated.

**Keywords**
root respiration, plant water status, soil water content

Accurate irrigation planning is an important part of modern agriculture. In the practice, it is mostly based on soil moisture determination or climatic water balance calculations (Krüger et al. 1999, Allen et al. 1998). Soil moisture measurements give information about the amount of water stored in the soil (volumetric soil water content) and/or its plant availability (soil water potential). Climatic water balance calculations estimate the potential evapotranspiration of a cropped area based on weather data and the possible and required amount of irrigation necessary to fill the soil water storage. Both approaches detect the irrigation demand of plants indirectly based on weather or soil data, but not directly at the plant itself.

In the framework of a research and development project, funded by the Federal Office for Agriculture and Food (BLE), root zone-$CO_2$ measurements and their suitability for irrigation scheduling in agriculture were investigated. The basic assumption was that plants reduce root respiration due to water limitation, which results in a WR-$CO_2$ decrease. Thus, irrigation water requirement should be directly measured at the plant by detecting a physiological response to water shortage. One advantage of this approach is the possible plant water status determination, enabling both stress avoiding irrigation and controlled deficit irrigation to improve fruit quality or water use efficiency. Another advantage is the non-destructive and continuous measurement, which bears all options for an automated irrigation.

## WR-$CO_2$ and $CO_2$ production in the soil

In this study, the term WR-$CO_2$ refers to the measured $CO_2$ concentration in a soil depth of 20 cm. In contrast, the $CO_2$ production in the soil reflects the actual total $CO_2$ production (roots respiration, microbial metabolism, etc.). Consequently, WR-$CO_2$ and $CO_2$ production within the same soil depth cannot be compared. The actual $CO_2$ production in soil depth Z is a function of the trends of $CO_2$-con-

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centration and $CO_2$-diffusion coefficient between soil surface and soil depth Z and thus only distinctly definable with these information (Schack-Kirchner et al. 2011).

## Plant-specific $CO_2$

The measured WR-$CO_2$ may only give a rough idea about the actual $CO_2$ production in the soil, but doesn't reflect it in quantitative terms. In addition, $CO_2$ production in the soil is not determined by the plants alone. Root respiration (autotrophic $CO_2$ production) results from the decomposition of carbonic compounds, produced during photosynthesis. Heterotrophic $CO_2$ production comprises the $CO_2$ production of all heterotrophic microorganisms in the soil (Kuzyakov 2006). Since heterotrophic microorganisms decompose root exudates as well, it is difficult to explicitly differentiate between "$CO_2$ production due to the plant" and "$CO_2$ production without plant". Therefore the term "plant-specific $CO_2$" ($CO_{2\text{-P}}$) was introduced. $CO_{2\text{-P}}$ comprises the total $CO_2$ production which can be directly or indirectly attributed to the plants.

The objective of the present study was basic investigations about the suitability of WR-$CO_2$ measurements for plant water status assessment and irrigation scheduling in agriculture.

## Material and Methods

The investigations were conducted in a growth chamber of the University of Hohenheim (Stuttgart, Germany). Object of the investigations were five 1.80 m high apple trees, planted in 20 l PVC pots filled with sandy loam. Mean daily temperatures in air and soil ranged from 18.5 to 22.4 °C and from 15.2 to 18.4 °C, respectively.

Soil water content within the pots was measured with dielectric sensors and logged on a PC in 10-minutes-intervals. Soil water potential data was measured with self-made tensiometers, equipped with pressure transducers (AO-1, Reisinger GmbH) and stored by a data logger (HOBO U12-008, Onset).

Water status references for the apple trees were measured between noon and 1pm with a Porometer (SC-1, Decagon Devices), with four replicates at randomly selected leaves of the same tree. In order to distinctly differentiate the trees with respect to plant water status, the relative stomatal conductivity ($rg_s$) was defined. $rg_s$ is obtained by dividing the actual measured stomatal conductivity of the investigated tree in drying soil ($g_{s,actual}$) by a reference stomatal conductivity ($g_{s,reference}$). $g_{s,reference}$ is measured at continuously well irrigated trees. That way decreasing $rg_s$ point to a change in plant water status due to water shortage.

$CO_2$ measurements are commonly realized with electrochemical (e.g. Figaro) or optical (infrared) techniques. The conducted $CO_2$ measurements were made with Infrared-Modules (SenseAir, K30) with a measuring range from 0 to 10,000 ppm. The $CO_2$ measurements were displayed on PC in a 5-minutes-interval with Terminal Emulator (Tera Term, V. 4.82) and subsequently logged. The required hardware was developed by Mannheim University of Applied Sciences.

$CO_2$ measurements in the root zone were performed with $CO_2$-modules in air-tight PVC tubes (Ø 63 mm, length 25 cm) and connected to a PC with airtight cable lead-troughs. The PVC tubes were installed in previously-made percussion boring installation holes. Air gaps between PVC tube and soil were closed in order to avoid artificial $CO_2$ pathways. The opening at the bottom of the PVC tube enabled WR-$CO_2$ inflow. The measuring depth of the PVC tube was 20 cm.

## Results and discussion

### Irrigation, soil water content and WR-$CO_2$

First investigations on an apple tree aimed on the influence of irrigation on WR-$CO_2$. Figure 1 shows that WR-$CO_2$ reacts to irrigation with a distinct increase. Immediately after irrigation, the values always exceed 10,000 ppm. Since the used $CO_2$-modules are restricted to a range from 0 to 10,000 ppm, their principle suitability had to be proved. Simultaneous measurements of soil water potential (Ψ) (not shown) revealed that WR-$CO_2$ dropped below 10,000 ppm at Ψ < -80 mbar (field capacity). At these Ψ values, water supply to plants is optimal, which is why the measuring range of the $CO_2$-modules is assumed being sufficient for further investigations.

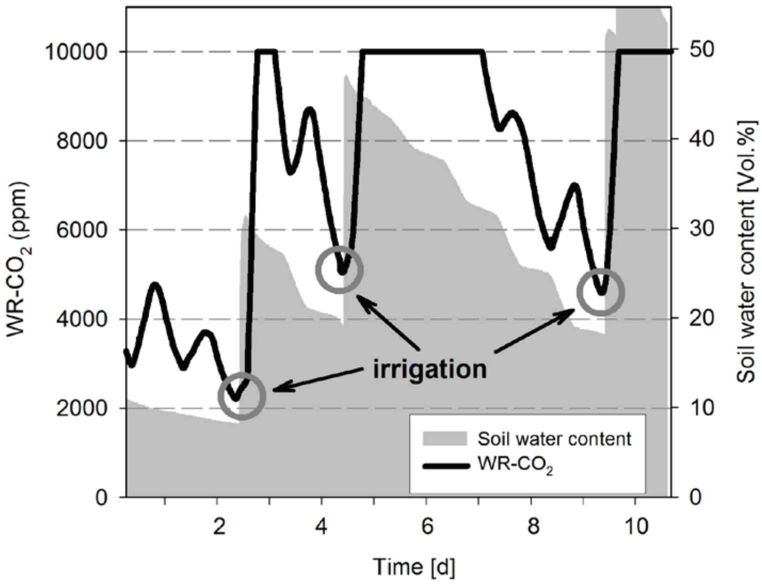


Figure 1: Influence of irrigation on WR-$CO_2$

A causal relationship between irrigation and distinct WR-$CO_2$ increase after irrigation is apparent (Figure 1). However, this WR-$CO_2$ increase cannot be explained solely with increased $CO_2$ production (e.g. root respiration) due to improved water supply. The process of soil gas transport should be additionally considered. As diffusion is the dominant $CO_2$ transport process in the soil and $CO_2$ diffusiveness in gaseous phase is $10^4$–$10^5$ times higher as compared to the diffusiveness in liquid phase (Maier and Schack-Kirchner 2014), soil water content (or air-filled porosity) plays a decisive role. Assuming Fick's law being valid in soil, gas flux between two points is determined by the gas concentration difference and the gas diffusion coefficient. A decrease of $CO_2$ diffusion coefficient due to irrigation will therefore lead to reduced $CO_2$ fluxes (Moldrup 2000). As a result, WR-$CO_2$ can increase even though $CO_2$ production did not change. The distinct WR-$CO_2$ increase after irrigation (Figure 1) suggested this effect. Irrigation water infiltrated soil, filled the soil pores and hindered $CO_2$ efflux. Whether and to what extent a $CO_2$ production increase contributes to the observed WR-$CO_2$ increase and whether this contribution is relayed with a time lag could not be determined.

Prompt WR-$CO_2$ increases after irrigation are followed by phases of decreasing soil water content. The development of soil water content obviously correlates with the WR-$CO_2$, which shows daily fluctuations with a decreasing trend (Figure 1). Following this observation an in-depth investigation with a further experiment was conducted. The soil of three apple trees was saturated. Then WR-$CO_2$ and soil water content were measured and logged during soil drying by root water uptake. The midday results (1 pm) are depicted in Figure 2.

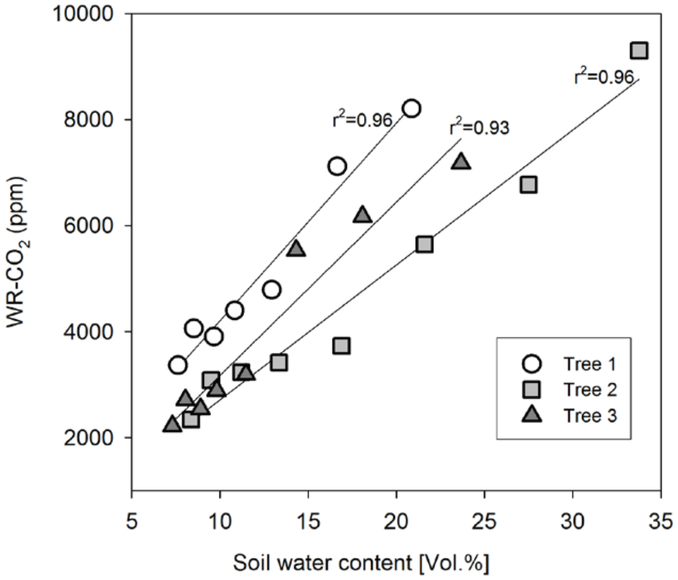


Figure 2: Midday values of WR-$CO_2$ (1 pm) and soil water content during soil drying of three apple trees

Results show for the soil drying phase a distinct positive correlation between WR-$CO_2$ and soil water content. Because plant water availability and plant water status correlate with soil water content (Intrigliolo and Castel 2004, Jones 2004), a WR-$CO_2$ based irrigation scheduling seems principally justified. It should be noted, however, that the use of one representative correlation is hampered by clear differences between the trees (Figure 2). These differences can be explained by the broad range of factors that influence WR-$CO_2$. A decrease of WR-$CO_2$ can be attributed to (i) an increase of the diffusion coefficient due to soil water content decrease, (ii) a decrease of $CO_2$ production or (iii) both of these factors, with spatially and temporally changes in weighting (Schack-Kirchner et al. 2011).

## Plant specific $CO_2$ ($CO_{2\text{-}P}$)

The high coefficients of determination between WR-$CO_2$ and soil water content (Figure 2) raised questions about the plant's contribution to the measured WR-$CO_2$ and whether $CO_{2\text{-}P}$ – especially root respiration – is sufficiently reflected by WR-$CO_2$. Following the "root exclusion method" (Hanson et al. 2000) the share of $CO_{2\text{-}P}$ on WR-$CO_2$.was determined by measuring WR-$CO_2$ in soil with and without plants. Figure 3 shows trends of soil water content, $CO_{2\text{-}P}$ and $CO_{2\text{-}B}$ ($CO_2$ in soil without plant). $CO_{2\text{-}P}$ was calculated as the difference between WR-$CO_2$ and $CO_{2\text{-}B}$. For WR-$CO_2$ midday values (1 pm) were used. $CO_{2\text{-}B}$ was measured in a soil with the same properties without plants. In order to obtain the desired soil water content, small amounts of water were stepwise added to the initially air-dry soil. Each time final values of soil water content and $CO_{2\text{-}B}$ were taken after 3 days. That way $CO_{2\text{-}B}$ was measured for 4 different soil water contents (saturation, 0.3, 0.2, 0.1) and matched to the experimental days (days after irrigation) 1, 2, 4 and 8. $CO_{2\text{-}B}$ data for the other days were calculated by linear interpolation.

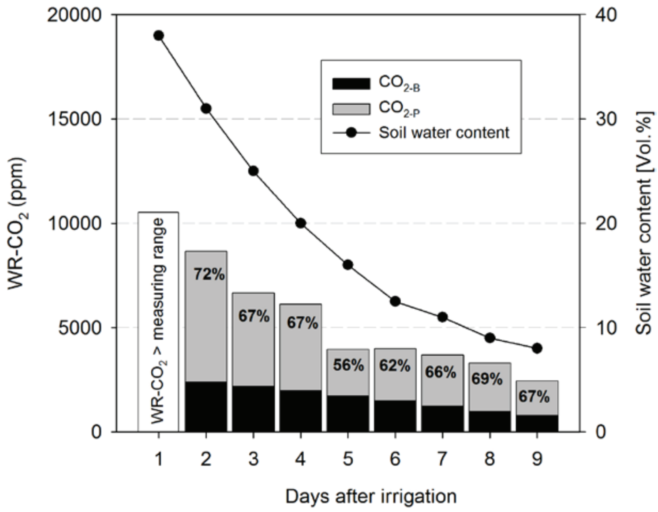


Figure 3: Shares of $CO_{2\text{-}P}$ (plant specific $CO_2$) and $CO_{2\text{-}B}$ (WR-$CO_2$ without $CO_{2\text{-}P}$) of an apple tree during soil drying. The percentage of $CO_{2\text{-}P}$ on WR-$CO_2$ is depicted in the bars

$CO_{2\text{-}P}$ and $CO_{2\text{-}B}$ could not be quantified at saturation, because the respective values were above the measuring range of the $CO_2$-modules. With decreasing soil water content, $CO_{2\text{-}B}$ decreases quickly to values around 2300 ppm. Beyond this point, there is only a slight decrease until values of 1000 ppm are reached. At any time and any soil water content, $CO_{2\text{-}P}$ is larger than $CO_{2\text{-}B}$. The percentage of $CO_{2\text{-}P}$ of WR-$CO_2$ varies between 56 and 72 % and is similar to results published by Edwards (1991) based on a similar result with pine trees (*Pinus teada*) (54–78 %). It can be stated, that $CO_{2\text{-}P}$ of the investigated apple trees contributes substantially to the WR-$CO_2$. In principle, the use of WR-$CO_2$ as measure for $CO_{2\text{-}P}$ seems to be justified.

## WR-$CO_2$ and plant water status

The final investigations aimed on the question, whether plant water status information of the investigated apple trees can be deduced from WR-$CO_2$ data. To answer this question, daily values of relative stomatal conductivity ($rg_s$) were determined and WR-$CO_2$ measured in a drying soil, starting from field capacity. The correlation of $rg_s$ and WR-$CO_2$ is depicted in Figure 4. While single trees show coefficients of determination of 0.80 (tree 2), 0.94 (tree 3) and 0.95 (tree 1) (not shown), the average coefficient of determination of all 3 trees is still 0.79. All 3 trees show largest $rg_s$ values (approx. 1.2) at highest WR-$CO_2$ values. The maximum WR-$CO_2$ ranged from 6200 ppm (tree 3) to 9300 ppm (tree 2). This means, that trees with optimal water supply might differ with respect to WR-$CO_2$. Down to an $rg_s$ of 0.5–0.6, which corresponds with half the stomatal conductivity of optimally irrigated trees, the $rg_s$ decrease goes along with a respective decrease in WR-$CO_2$. Below this point, $rg_s$ partly decreases further, while WR-$CO_2$ does not. Obviously, a point was reached with minimum $CO_2$ production and concurrent maximum in $CO_2$ diffusion. Both can serve as an explanation as to why WR-$CO_2$ does not decrease below a certain threshold, whereby this threshold depends on plant as well as on soil. A sound weighting of both influencing factors is not possible with the current data.

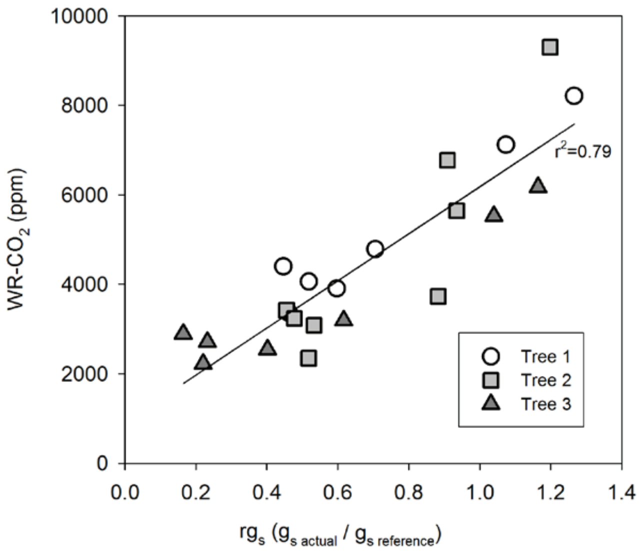


Figure 4: Correlation between WR-$CO_2$ and relative stomatal conductivity ($rg_s$)

## Conclusion

The presented results show that WR-$CO_2$ and soil water content of the root zone are correlated with each other. Further, it was shown that under the prevailing conditions of the experiment, a large share (56–72 %) of WR-$CO_2$ originates from the crop under observation and changes in WR-$CO_2$ are correlated to changes in the stomatal conductivity.

The continuous measurement of WR-$CO_2$ with a specially designed sensor shows new opportunities with respect to real-time detection of aspects along the soil-plant-air continuum. Further investigations are necessary, since the limited sample size underlying the presented results does not allow for a final description of the critical WR-$CO_2$. For continuation of the research, particular emphasis will be on the identification of values of critical water supply, which can be used for optimization of irrigation scheduling and on the determination of appropriate algorithms for automatic data evaluation and plant water status calculation. Furthermore, investigations will be expanded to other crops.

Even though the presented data do not allow a final conclusion on the suitability for practice, it could be demonstrated, that real-time detection of WR-$CO_2$ has a potential for irrigation planning and scheduling.

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