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Storage of Intercepted Water on Vegetable Plants Measured by Gamma Scanning Technique

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Summary

An estimate of water losses caused by canopy interception is required to calculate soil water balances or to parameterise models of crop water demand. A gamma-scanning technique allows to measure non-destructively and accurately as well as continuously over a short-time period the amount of intercepted water in a vegetable crop canopy. To evaluate intercepted amounts, spinach (*Spinacia oleracea* L. var. *foliosum* Hegi 'Boeing') canopies were treated with controlled amounts of irrigation water supplied by a sprinkler (to simulate rain and irrigation conditions) or a nozzle (to reproduce dewfall and wetting agents used in plant protection). For plant masses from 1.5 to 5.0 kg m^{-2}, the storage of water was from 0.25 to about 1.00 mm when water amounts from 3 to 21 mm were applied by sprinkler. Using amounts of 0.38 and 0.75 mm water supplied by nozzle, the interception increased from 0.05 to almost 0.40 mm for spinach fresh masses between 0.25 and 2.25 kg m^{-2}. Here, we assume that the accuracy of mass determination of spinach is equivalent to broccoli that was examined in a previous study by weighing broccoli plants at different growth stages. The error of measurement was estimated within <5 % for fresh plant masses of about 0.100 kg m^{-2}, and within <1 % for masses >1.25 kg m^{-2}.

Zusammenfassung

Messung des Haftwassers an Gemüsepflanzen mit Hilfe der Gamma-Scanning-Technik. Die Bestimmung der Wasserverluste durch Interzeption an Pflanzen ist für die Berechnung von Wasserbilanzen oder die Ermittlung von Parametern in Modellen zum Wasserbedarf bedeutsam. Die Anwendung der Gamma-Scanning-Technik erlaubt es, zerstörungsfrei, sehr genau und kontinuierlich in kurzen Zeitabständen die Menge von Haftwasser an Gemüsepflanzen zu messen. Spinatbestände der Sorte 'Boeing' wurden mit definierten Mengen an Beregnungswasser mittels eines Regnersegmentes mit Tropfschläuchen (zur Simulation von Niederschlag oder Bewässerung) oder mit einer Düse (zur Simulation von Tau oder Befeuchtung beim Pflanzenschutz) behandelt. An Pflanzenbeständen mit Massen von 1.5 bis 5.0 kg m^{-2} haftet eine Wassermenge von 0.25 bis etwa 1.00 mm, wenn 3 bis 21 mm mit dem Regnersegment ausgebracht werden. Bei der Ausbringung von Wasser mit der Düse in den Mengen von 0.38 und 0.75 mm liegt die Menge an Haftwasser bei 0.05 bzw. bei 0.40 mm für Spinatbestände mit Frischmassen von 0.25 bis 2.25 kg m^{-2}. Es kann angenommen werden, dass der Fehler für die Massebestimmung <5 % beträgt, wenn Pflanzenbestände von etwa 0.100 kg m^{-2}, untersucht werden und <1 % beträgt, wenn Bestände von >1.25 kg m^{-2} untersucht werden, wie dies bei Messungen an Brokkoli zu verschiedenen Wachstumsstadien zuvor ermittelt worden ist.

Key words. canopy storage capacity – radiometric measured plant mass – sprinkler and nozzle irrigation – *Spinacia oleracea* L.

Introduction

The rainfall interception by plants is a significant component of water dynamics in forests, agriculture, and horticulture. Canopy interception losses of precipitation or irrigation water are of relevance to many hydrological investigations (DUNKERLEY 2000). An estimate of water losses caused by canopy interception is required to calculate soil water balances or to parameterise models of crop water demand. Additionally, plant pathologists are interested in time courses of canopy wetness, which are dependent on climatic conditions.

Most literature on interception water losses deals with forests. Using a gamma ray attenuated technique, CALDER and WRIGHT (1986) measured forest canopy mass and water storage in Sitka spruce (*Picea sitchensis*).

The applicability of microwave attenuation measurements for the determination of canopy wetness, was examined by BOUTEN et al. (1991, 1996). This system can be used for forest hydrological studies and is also suitable for unattended automated scanning of canopy water storage as well as to measure the duration of leaf wetness and dynamics of the internal water content of trees.

DUNKERLEY and BOOTH (1999) suggested that grass communities forfeit 30 % of annual rainfall to interception of rain in arid areas of Australia. A similar estimate (27.2 % loss), was reported by NAVAR and BRYAN

(1990) for a semi-arid Mexican shrub-land; however, far lower values have also been estimated for the interception storage capacity in a variety of dry-land plants (NAVAR and BRYAN 1990). DUNKERLEY (2000) highlighted that models have been only rarely applied to dry-land plant communities, and that direct measurement techniques need additional testing and refinement before being applied in the field.

Very few studies have been conducted to measure the interception of irrigation water by agricultural and vegetable plants. SCHAEFER and KOITZSCH (1974) used a single sprinkler set-up in the centre of a white plastic sheet with "planted" sugar beets nailed on wood laths and estimated water losses by interception to be up to 0.14 mm. VON HOYNINGEN-HUENE (1983) used a stem-flow gauge along with sub-canopy waxed channels to measure interception of rain by corn, wheat, rye, oat, potato, sugar and fodder beets. Interception water losses by silage maize, sugar beet and oat crops grown in the Baltic coast region were measured to be 29, 47 and 48 % of total precipitation, respectively (SCHMIDT and MUELLER 1991). The losses were mainly determined by the amount, intensity, and distribution of rainfall along with the rate of change of leaf area during the growing period.

WIGNERON et al. (1996) analysed the time variations of microwave emissions during irrigation phases in a wheat field. Low-frequency microwave measurements were used to monitor hydrological variables over a wheat crop, i.e. surface soil moisture and water interception by the vegetation canopy. The value of the wheat water storage capacity was in good agreement with experimental data based upon direct measurement techniques.

VAN DIJK and BRUIJNZEEL (2001a, 2001b) described an analytical model to predict rainfall interception by sparse canopies. An application of this is presented to simulate throughfall, stemflow and interception as measured in a mixed agricultural cropping system involving cassava, maize and rice in upland West Java, Indonesia. Measured interception losses were calculated to be 18 and 8 % for two different measuring periods.

Very little work has been performed to measure the water interception of vegetable plants. HARTMANN (1993) weighed fresh carrot, cauliflower, celery, lettuce, and leek plants after harvest and then nailed desired plant densities on laths. Irrigation amounts of 20 mm were applied by watering can and the plant material was weighed two minutes later after the draining of surplus water. The interception storage capacity reported ranged from 1.50 to 5.25 % depending on plant mass and cultivar.

A general search of the ISI WEB OF KNOWLEDGE (2003) for references on interception of vegetable plants produced no result. This is surprising as water interception and the calculation of the variables involved are key data for optimised vegetable plant production. For vegetables, water storage and wetness are one of the fundamental variables in the within-canopy microclimate. Microclimatic conditions strongly influence the plant's health and growth as the local and temporal persistence of wetness on the surface of the plants are associated with the incidence and spread of sporulate fungal pathogens (JAMES et al. 1984; LECLERC et al. 1985; WEI et al. 1995).

Different techniques have been used to measure canopy water storage for agricultural crops and forest canopies, and consequently, large discrepancies are observed between the reported data. Therefore, none of the previously described techniques has become a reference method. To overcome this problem, this paper describes a gamma ray scanning technique that has the key benefit of allowing the quantity of intercepted water to be measured non-destructively and accurately as well as continuously over a short-time period. Measurements were made on spinach plants and were taken in the field.

Materials and Methods

Experimental site and plant material

Spinach (*Spinacia oleracea* L. var. *foliosum* Hegi 'Boeing') canopies in a box frame plot installation at the experimental station of the Institute of Vegetable and Ornamental Crops in Grossbeeren (52.03 °N, 13.31 °E, latitude about 30 m a.s.l., near Berlin), Germany were used. The plot size was 2 by 2 by 0.75 m (depth). Plots were buried in the ground, concrete sides added and then each was filled with a 0.25 m layer of gravel-sandy soil and covered with 0.50 m diluvial sand (Gleyic cambisol). To avoid edge effects of evaporation, the selected plots were enclosed in a group of total 24 plots planted with different kinds of vegetables under irrigation.

A movable roof offered protection from rainfall and drainage tubes were installed to remove excess water.

In 2000 and 2001, spinach was sown in May and July for spring and autumn measurements, respectively. In accordance with the production reference in Germany, the spacing was 0.20 m between rows and 0.03 m between plants in the row (estimated mean plant density was 170 ± 6.9 plants m^{-2}).

To imitate natural rainfall in the field, water was applied either by sprinkler or nozzle (Fig. 1) mounted at the top of a 0.75 m high sprinkler machine, connected to an electronic unit and electric motor for horizontal travel. It is constructed using a span of aluminium pipe, 2.00 m long. 25 small rubber tubes, diameter 1.5 mm and 10 cm long, are mounted at distances of 8 cm. By a special nozzle (Type: DAN 8991 kassproeier, nozzle diameter 1 mm, REVAHO, The Netherlands) the wa-

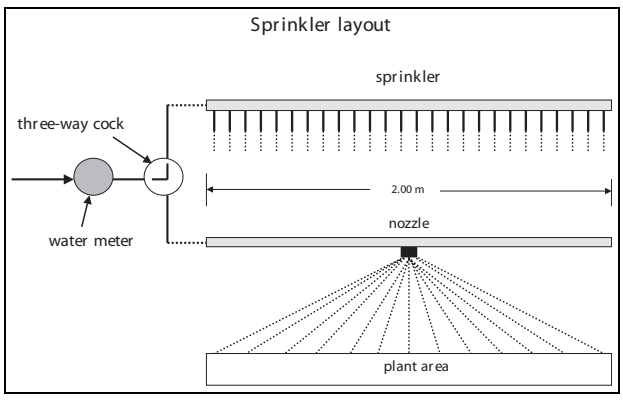


Fig. 1. Sprinkler layout used to obtain interception measurements either by sprinkler segment with tubes or by nozzle.

ter, is transformed into a fine and uniform mist to reproduce dewfall and wetting agents used in chemical plant protection. Water amounts were distributed on the spinach canopy in doses of 1x3 mm, 1x7 mm, 2x7 mm and 3x7 mm and nozzle water doses were 0.38 mm and 0.75 mm. The amount of irrigated water applied by the sprinkler machine was regulated by different pressure values, which were registered on a pressure gauge. Different levels of water application were measured by a water meter. The time step for one irrigation procedure was 105 s per plot.

Definition of interception

The precipitation interception is defined as "Part of precipitation or sprinkler irrigation system applied water (in., mm) caught on the vegetation and prevented from reaching the soil surface" (NRCS 1997). In our case, the interception equals the part of total applied irrigation water on the vegetation minus stem flow and through-fall.

The irrigation water on spinach, stored on the surface of the leaf and stem components, increased proportionally with aboveground fresh mass. The amount of intercepted irrigation water was estimated by calculating the difference of radiometric measured fresh mass of dry canopy before irrigation (i.e. no water on the plants) and fresh mass of wet plant canopy measured about three minutes after one irrigation cycle.

Principle of measurement, gamma-scanning trolley and measurement procedure

This non-destructive measurement utilises the absorption of gamma rays passing through plant material. The absorbed gamma rays are in accordance with the mass attenuation law (PRICE et al. 1957).

The gamma-scanning trolley is designed to span between two rigid rails, providing the required constancy of measuring dimensions (Fig. 2). Four gamma americium sources (^{241}Am, 3.7 GBq activity each, 4 mm diameter, type: AMCP1 of Amersham Laboratories, England) are mounted at 9 cm intervals in one block. The four scintillation detectors (sodium iodide crystal, 3.6 cm in diameter) are connected to four photo-multipliers and are mounted on the opposite side of the plant area in the same way (GUTEZEIT 2000).

For the first scanning procedure, plant fresh mass was measured simultaneously in horizontal layers spaced 3 cm apart: (1) layer 1 is the lowest installed gamma source-detector line (gamma source = 1, scintillation detector = 1); (2) layer 4 is over the lowest installed gamma source-detector line (gamma source = 2, scintillation detector = 2, plant height = 9 cm); (3) layer 7 (gamma source = 3, scintillation detector = 3, plant height = 18 cm); and (4) layer 10 (gamma source = 4, scintillation detector = 4, plant height = 27 cm). The second procedure, layers 2 (plant height = 3 cm; over the lowest installed gamma source-detector line), 5, 8, and 11 were scanned. Finally, and during the third procedure the layers 3, 6, 9, and 12 were scanned. After three vertical steps, a plant height of 33 cm is scanned. Plant height above 33 cm can be measured by scanning layer 13 upwards. The selected scanning speed in the experiment was 2.99 cm s^{-1}, but it can be varied if required.

It is assumed that accuracy of mass determination of spinach is equivalent to broccoli that was examined previously (GUTEZEIT 2000). The accuracy for mass determination on plants was estimated by (1) comparison of the radiometric measured fresh mass of canopies between four and nine repeated measurements depending on fresh mass amount after transplanting and the following growth stages until harvest, and (2) weighing (gravimetric mass). After the last scanning procedure, the total mass of each plot was determined by weighing the mass (without replication) of all plants cut horizontally by a thin wire fixed under the lowest installed gamma source–detector line. The error of measurement was calculated to be <5 % for fresh plant masses of about 0.100 kg m^{-2}; whereas those, which were >1.250 kg m^{-2}, had a calculated error <1 % (GUTEZEIT 2000).

Calibration procedure for spinach plants

To determine the correlation between the radiometric plant mass and the gravimetric plant mass, studies were performed on plants using different growth stages on different times as well as different growth stages on the same time by weighing spinach plants. The total spinach plant mass of the plot was determined by weighing the mass after cutting.

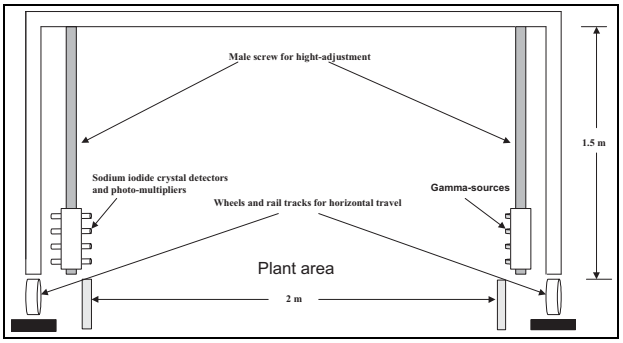


Fig. 2. Gamma-scanning trolley used to obtain non-destructive measurements of the mass of fresh spinach plants.

Results and Discussion

Relationship between radiometric measured mass and fresh mass

A comparison of measured and weighed masses for the 18 data sets generated here are presented in Fig. 3. A highly significant linear relationship (correlation coefficient r=0.985) was found between the radiometric measured plant mass after measuring the plant canopy using the gamma-scanning device, and the plant mass determined gravimetrically by cutting and weighing. If a mean water content of 92 % for fresh spinach plants (GEBHARDT and THOMAS 2000) is assumed, then the error for the estimated intercepted water corresponds to the calculated fresh plant masses. Note that in fresh broccoli plants, mean water contents of 90 % for head and 92 % for leaves and stems were previously estimated (GUTEZEIT 2004) and are in line with those of GEBHARDT and THOMAS (2000).

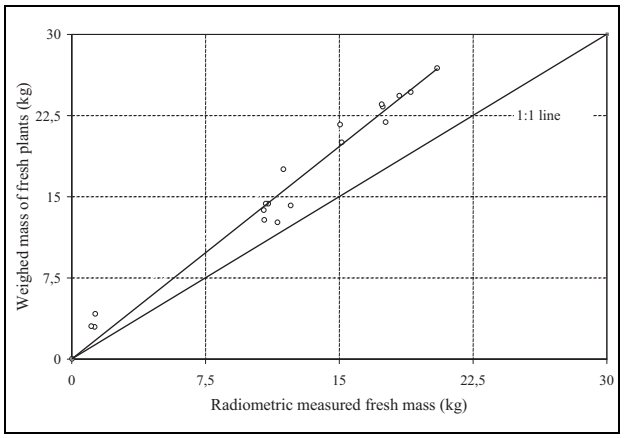


Fig. 3. Relationship between radiometric mass R_m and weighed mass M_w of fresh spinach plants; prediction equation is M_w=1.3088 R_m for n=18; correlation coefficient r=0.985.

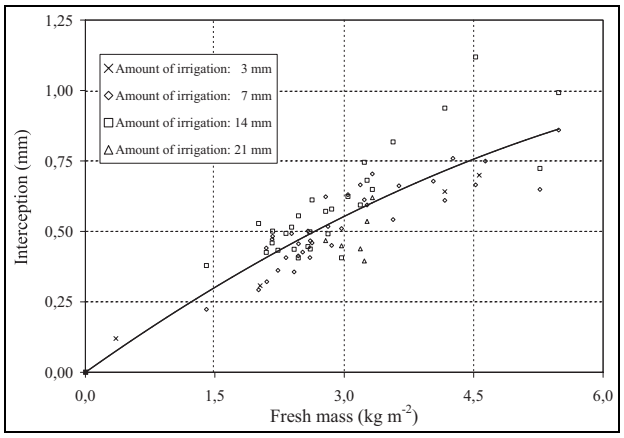


Fig. 4. Interception (canopy storage capacity) in dependence on the mass of fresh plants and irrigation amount. Irrigation water was applied by a sprinkler segment with small tubes.

Interception of water applied by sprinkler

BARFIELD et al. (1973) reported that irrigation drop sizes of >1x10^{-3} mm had no significant effect on the surface water storage capacity of individual leaves of lettuce, cucumber and tomato plants. MARSHALL and PALMER (1948) obtained drops of 1.0 to 3.5 mm diameter by analysing rain intensities of 1 to 23 mm h^{-1}. Therefore, using tubes of 1.5 mm-diameter with the sprinkler segment, irrigation amounts represent a typical "rain event" in agreement with SEED et al. (1996) estimated drop size radius between 0.50–1.80 mm.

During irrigation and the measurement procedure, the maximal error (water loss by evapotranspiration) was lower than 0.12 mm. Moreover, using the maximal sum of the reference crop evapotranspiration ETo in Grossbeeren, as estimated by the German Weather Bureau, Agricultural Service, a ETo=6.2 mm day^{-1} can also be expected. Therefore, due to condensation, the total evapotranspiration of 6.2 mm day^{-1} for a 14 light hour day, which would allow a maximum of three irrigation applications and three subsequent scanning measurements of one plot required 6 and 10 min, respectively, and resulted in a total evapotranspiration of 0.12 mm.

The results of the sprinkler applied experiments with amounts of 3, 7, 14 and 21 mm are shown in Fig. 4. The interception increased with plant mass. When the spinach canopy of a fresh mass of 1.5 kg m^{-2} (equivalent to a leaf area of about 2 m^2 m^{-2}, Fig. 6, estimated at the experimental station of the Institute Grossbeeren by DEIL 2003) was exposed to a water amount from 3 mm to 21 mm, the interception was about 0.3 mm. The interception rose from around 0.6 mm to 0.8 mm for plant masses of 3.0 kg m^{-2} (equivalent to a leaf area of 4 m^2 m^{-2}) and 5.0 kg m^{-2}, (equivalent to a leaf area of 7 m^2 m^{-2}), respectively. When the plant canopies of same fresh mass had been adequately applied with water by the first irrigation only, the second and third irrigations caused no additional of water storage. Drops coalesced on plants and become heavy enough to slide down the plant surface; thereby, decreasing the percentage of interception. When the irrigation amounts increased to 21 mm, the percentage decreased to 4 % for plant masses of 5.0 kg m^{-2}, compared to 11 % for irrigation amount of 7 mm. This is in accordance with HARTMANN (1993) who reported for 20 mm water depth that crop leaf retention varied between 1.50 and 5.25 % for cauliflower and lettuce, respectively, as measured on ripe harvested plants. LEUNING et al. (1994) estimated the rainfall storage capacity of green wheat, which is highly dependent on the stage of development of the canopy, to be about 1–2 mm m^{-2}. Interception water losses (percentage of interception) accounted for 33 % of rain during a period (114 mm).

RICHE and CHRISTIAN (2001) measured for *Miscanthus giganteus* (a tall perennial tropical grass), which is currently being evaluated throughout Europe for possible commercial application in biofuel production, that the mature crop forms a dense leaf canopy and intercepts a high proportion of rainfall. They also predicted that over one year, the net rainfall under *Miscanthus* would be about 20 % less than the gross rainfall; thus, allowing more water to be available to other plants. NAETH et al. (1991) found that litter and organic matter accumulations can reduce soil water through interception of precipitation and subsequent evaporation of adsorbed water. Interception varies with mass and water holding capacity (WHC) of litter and organic matter, and is highest for small precipitation events.

SCHMIDT and MUELLER (1991) report on the analyses of precipitation losses due to interception by silage maize, oat and sugar beet crops, based on observations in the Baltic coastal region (Germany) in 1979–81 and 1985–86. Average losses were 29, 47 and 48 % of total precipitation for maize, sugar beet and oats, respectively. The losses were mainly determined by the amount, intensity, and distribution of rainfall as well as the rate of change of leaf area during the growing period. If enough water was applied, drops coalesced and become heavy enough to slide down the plant surface. Also, in the laboratory, rainfall simulation experiments using rainfall intensities of 25.4 to 127 mm h^{-1} had little effect on the rate of rainfall interception by corn and soybean residue (MOHAMOUD and EWING 1990).

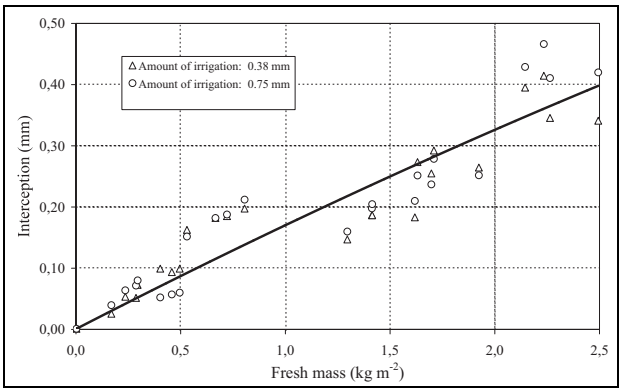


Fig. 5. Interception (canopy storage capacity) in dependence on the mass of fresh plants and irrigation amount. Irrigation water was applied by a nozzle.

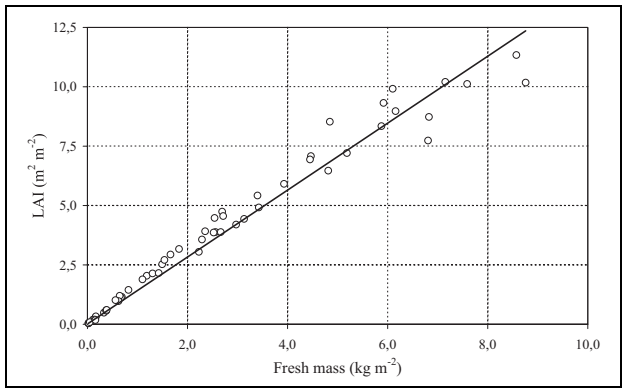


Fig. 6. Relationship between mass of fresh plants (F_m) of spinach and leaf area index (LAI), data of DEIL 2003; prediction equation is $LAI=1.4091F_m$ for n=57; correlation coefficient r=0.983.

Moreover, BUTLER and HUBAND (1985) found no significant differences for both rain and irrigation measurements for spring and winter wheat. Therefore, we assume that the results of the water storage on spinach plants, using our approach along with irrigation procedure, represent the effect of irrigation and precipitation (restricted) under field conditions.

Interception of water applied by nozzle

In the second experiment, water was applied by a nozzle to the spinach surface. Irrigation amount of 0.38 mm were stored totally on spinach canopies for masses of more than 2.25 kg m^{-2} (Fig. 5), equivalent to a leaf area of about 3 m^2 m^{-2} (Fig. 6).

For rain events or irrigation amounts that fail to saturate the vegetable canopy store, a reason may be that some of the water may be held on the leaves. When the spinach canopy was exposed to a further water amount of 0.37 mm (total amount 0.75 mm), the plant canopy stored about 0.4 mm. The irrigated water is stored on the upper surface of leaves and stems up to their maximum storage capacity, above which, a part of the water is delivered by drops or stem-flow to wet the soil and root zone.

The results of this experiment (Fig. 4 and Fig. 5) show the high potential of the measurements for monitoring the storage of water on spinach plants in relation to fresh mass and water amount for both irrigation principles.

Concluding Remarks

The presented gamma-scanning technique demonstrates the feasibility of estimating the interception of water amount from irrigation or precipitation; an important hydrological variable in regards to a vegetable crop field. A highly significant linear relationship (R^2=0.970) was found between the radiometric measured plant mass and the plant mass determined gravimetrically by cutting and weighing. The quantity of intercepted irrigation water increased during canopy development, i.e. with increasing plant surfaces. For plant masses from 1.5 to 5.5 kg m^{-2}, the canopy storage capacity increased from 0.25 to about 0.80 mm when water from 3 to 21 mm was applied. VAN DIJK and BRUIJNZEEL (2001b) estimated a canopy storage capacity of <0.26 mm for maize (*Zea mais*), <0.091 mm for cassava (*Manihot esculenta*) and <0.066 mm for rice (*Oryza sativa*) for leaf area indices of 0–0.3, 0–1.4 and 0–1.5, respectively. Our results indicate that the interception losses of spinach plants rose to about 0.80 mm with increasing leaf area index to about 10.

Water amounts of less than 1 mm applied by a nozzle, increased the interception to about 100 % for plant masses greater than 2 kg m^{-2}. Interception water losses during rain or irrigation events are deposited on the surface of leaves and stems up to their maximum storage capacity, above which the excess water falls to the ground.

It is evident that micro-scale variability in canopy conditions can have a large impact on plant health and productivity. Input data about the wetness distribution on plant canopies have been provide for modelling plant damage and decreases (HUBER 1988; DUTHIE 1997; WILSON et al. 1999). For these models, measurements of the distribution of incident rainfall or irrigation need to be supplemented by wetness persistence on plant surfaces. DUNKERLEY (2000) stated: "Models have been applied only rarely to dry-land plant communities, and direct measurement techniques are in need of additional testing and refinement. Research needs in this area are highlighted". In principle, the technique described here, could be used quasi-continuously at small time intervals on the same canopies, and allow the assessment of spatial distribution of intercepted water, dew or water loss by evaporation on vegetable, agricultural and ornamental plants and some sort of shrubs. A previous study on broccoli (GUTEZEIT 2000) and the results of this work show that further experiments and analyses will enable the resolution of the spatial distribution and evaporation loss of intercepted water on separate canopy layers.

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